PERFORMANCE OF BATTERY AND ULTRACAPACITOR AT VARIOUS TEMPERATURES

By

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FINAL PROJECT REPORT

Dissertation submitted in partial fulfillment of
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CERTIFICATION OF APPROVAL

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Electrical & Electronics Engineering Programme
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UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Syazreen binti Zainuddin

ABSTRACT

Battery is important for generating and storing electrical energy. It is sold at a rate of several billions of dollars per year worldwide. Battery can be found in nearly all motor vehicles, all types of portable electronic equipment, smoke alarms and others. However, it has a limited number of charge and discharge cycle because the process involves chemical substances. These chemical reactions have parasitic thermal release that cause battery to heat up and initiate unwanted reaction that could affect the batteries performance. With the emergence of technology, ultracapacitor is developing. Research has been proven that ultracapacitor have many advantages such as long life cycle, high charging and discharging rate, high capacitance in a small size and wide temperature range. However, people are not venture to looking and comparing the performance of ultracapacitor and battery at various temperatures. This project investigates the battery, ultracapacitor and battery-ultracapacitor (B-UC) combination performance at various temperatures. The main activity is to design the best equivalent circuit modes for battery standalone, ultracapacitor standalone and B-UC combination to be tested at various temperatures. Throughout this project, a working prototype of operating circuit consisting of battery, ultracapacitor and the Light Emitting Diode (LED) as a load will be constructed. Data Studio software with combination of Science Workshop 750 interface is used to verify the graph of current and voltage produced in the equivalent circuit model. In this project, the finding in this research indicates the ultracapacitor standalone supersite the performance of battery standalone with regard when tested at various temperatures.

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LIST OF ABBREVIATION

B-UC Battery-Ultracapacitor

LED Light Emitting Diode

DC Direct Current

AC Alternating Current

RC Resistor-Capacitor

EDLC Electric Double Layer Capacitor

ESR Equivalent Series Resistance

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Nowadays, battery has become a dominant power source for most applications and devices because it can store large amounts of energy in a relatively small volume, weight and provide suitable levels of power for many applications such as laptop, cell phone and radio. Battery can store large amounts of energy density, but often provide insufficient power density for applications where the load draws large power impulse such as GPS tracking system, RFID equipments, music players as well as vehicles [1].

Battery has a limited number of charge and discharge rates because the process involves chemical reactions with non-instantaneous rates. These chemical reactions have parasitic thermal release that causes the battery to heat up and initiate unwanted reactions that could affect the battery performance. Moreover, battery contains hazardous material that must be kept out of the environment [2].

These limitations have led to the design of ultracapacitor. Ultracapacitor is a kind of electrical energy storage device. It is governed by the same fundamental equations as conventional capacitor, but utilizes higher surface area electrodes and thinner dielectrics to achieve greater capacitances. This allows for energy density than those of the conventional capacitors and power density greater than the batteries [3].

1.2 Problem Statement

There are some weaknesses of the battery which require attention and action in order to improve its performance.

- Battery has a limited number of life span. It has a degrading performance due to chemical reaction within the battery.
- Battery cannot withstand high and low temperatures as these affect the internal resistance and efficiency of the battery and lead to poor performance of the battery.

1.3 Objective and Scope of Study

This project is aimed to study the effects of battery, ultracapacitor and B-UC combination performances in terms of its ability to provide enough current to the loads at various temperatures. Researchs have found that the combination of battery with ultracapacitors can prolong battery run time [4]. Thus, this project will be in greater detail experimentation to analyze the performance of both battery and ultracapacitor at various temperatures based on the recommendation from Research & Development Division, Perodua Rawang.

This project covers designing and constructing a circuit of a working prototype consisting ultracapacitor and battery which will be connected to a LED as the load. Experiments will be done at different temperatures. All the software available such as Multisim and Data Studio with the combination of ScienceWorkshop 750 interface is fully utilize to obtain the graph and table from the experimental circuits. This study involves analytical calculations of electrical parameters to support the circuit designed.

1.4 Relevance of the Project

The study of the effect of temperature in battery, ultracapacitor and B-UC combination is very important especially in automotive industry. It is because the results obtained from the laboratory experiments will help to give a better understanding of the behavior of battery and ultracapacitor at different temperatures. According to engineers of Research and Development Division in Perodua Rawang, Perodua has not produced any hybrid cars because research has not been done. A thorough understanding on the effect of temperatures in battery and ultracapacitor will provide useful information and further may contribute to having a much better reliable prediction leading to a cost-effective and safe design hybrid car.

1.5 Feasibility of Project

The project started by collecting reading materials such as books, journals and technical papers specifically on the effect of temperatures in battery, ultracapacitor and B-UC combination. Research is done continuously to get a better understanding on this project. The project focuses on designing a circuit and conducting experiments at different temperatures. Data Studio with the combination of ScienceWorkshop 750 interface is used to obtain the graph and table from the experiments. This project is scheduled to be completed the allocated time frame.

CHAPTER 2

LITERATURE REVIEW

2.1 Battery

Volta's invention of the Volta pile in 1800 represents the beginning of the field of battery science and engineering [5]. Battery is a device that converts chemical energy to electrical energy. Many portable electrical and electronic devices are designed to be powered from battery.

Current applications of batteries are very wide. However, there are some weaknesses of the battery which require attention and action in order to improve its performance. Battery has high equivalent series resistance (ESR) that is too large to continue to deliver high power pulse constantly. As it has an insufficient power density, it has difficulties delivering short high pulse current without battery becoming damaged, especially at low temperature [6].

Furthermore, battery also has a limited number of life span with a degrading performance due to the chemical reactions inside the batteries. The chemical reactions have the major influence on the aging of batteries as it causes the batteries to heat up and initiate unwanted reactions that could affect the battery performance.

All types of batteries are now widely classified as toxic waste and disposal of batteries is regulated. Improper disposal of all the batteries could be negatively affect the humans and environment as they contain dangerous chemicals such as mercury, cadmium, lead, nickel and lithium [4].

2.1.1 Categories of Battery

Battery is divided into two groups which are primary battery and secondary battery.

1. Primary Battery

Primary battery is a familiar kind of battery which has a fixed amount of energy stored in it during manufacture. Once that energy has been used up, the battery is simply thrown away and replaced [7]. There are many types of primary battery such as carbon-zinc battery, alkaline battery and zinc-chloride battery. Each type has its own strengths and weaknesses.

Figure 2.1: Primary battery

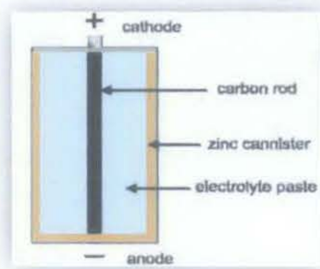

Figure 2.2: Cross sectional view of primary battery

2. Secondary Battery

Secondary battery is also known as rechargeable battery. It contains active materials that can be regenerated by charging. It is commonly used in mobile phone, vehicle and laptop. Some types of secondary battery are lead acid battery, lithium-ion battery and nickel cadmium battery.

Figure 2.3: Secondary battery (Lead acid battery) [8]

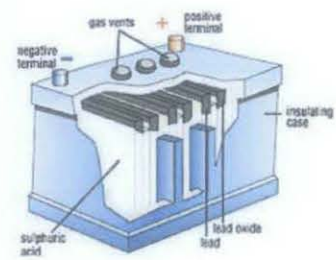

Figure 2.4: Cross sectional view of secondary battery [9]

2.1.2 Temperature Effect on Battery

Extreme weather affects the operation of the battery. The recommended operating temperature range for battery is -18 ℃ to 55 ℃. However, the battery performance is still impacted by temperature within the recommend range [10].

Chemical reactions in the battery are driven either by voltage or temperature. The hotter the battery, the faster chemical reactions will occur. The performance of the battery increases with high temperature, but at the same time the rate of the unwanted chemical reactions will increase resulting in a corresponding loss of battery life [2]. The combination of a rapid temperature change and high humidity can cause condensation to form a potential hazard for battery [10].

2.2 Capacitor

Capacitor is a fundamental electrical circuit element that store electrical energy. Capacitors have two main applications which are to charge or discharge electricity and to block the flow of direct current (DC). It is necessary for circuits to have capacitor where excellent frequency characteristics are required [11]. Capacitors are commercially available in different values and types. There are described by the dielectric material used and by whether they are fixed or variable type.

A simplest classic capacitor is constructed using two metal plates which are sandwiched close together with an insulator such as a vacuum, paper or other insulating material in between them. Two plates are connected to them which one plate to the positive pole of a power source and the other to the negative pole [12]. The capacitor and the schematic of capacitor are as shown in Figure 2.5 and Figure 2.6 respectively.

Figure 2.5: Capacitor

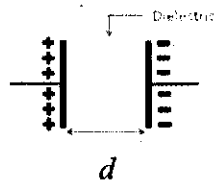

Figure 2.6: Schematic of capacitor

2.2.1 Capacitance in Capacitor

Capacitance, C is capability to hold an electric charge in a capacitor. Capacity may be commonly expressed as follows [13]:

$$C = Q/V \tag{1}$$

Q = Quantity of electricity
C = Capacity of capacitor
V = Electrical voltage

The capacity of a capacitor is dependent on the size and space of the conducting plates and the type of insulating or dielectric medium between the plates. The capacitance equation is as below [14]:

$$C = \varepsilon A / d \tag{2}$$

C = Capacitance in farad, F
ε = Dielectric constant ($\varepsilon_0\varepsilon_r$)
ε_o = Space permittivity (8.854×10^{-12} F/m^2)
ε_r = Relative permittivity
A = Area of one plate in square meters, m^2
d = Distance between plates and electrolyte

Capacitance is directly proportional to the plates' surface area but inversely proportional to the separation between plates. Through this equation, it is clear that by maximizing the surface area of the plats will give higher capacitance. The unit of capacitance is Farad (F) but typically, capacitor only has values in picoFarad (pF) to microFarad (μF) range.

2.3 Ultracapacitor

Ultracapacitor is also known as supercapacitor or Electrolytic Double Layer Capacitor (EDLC). The use of capacitors as the energy storage devices only became possible with the invention of ultracapacitor in late 1960. Fundamentally, ultracapacitor consists of two metal plates separated by an insulator just like a conventional capacitor in Figure 2.5. However, the separator of the ultracapacitor is soaked and porous in an electrolyte, which allowed negative and positive ions move freely in opposite direction to their respective electrodes.

The advantages of ultracapacitor are long life cycle, high charging and discharging rate and high capacitance in a small size. These advantages offer an ideal option for high power applications such as hybrid power system, power generator, vehicles and computer system. A parallel configuration of a battery and ultracapacitor will improve the power density of hybrid supply, reduce internal losses and also extend the discharge life of the battery [15].

Ultracapacitor is based on the existing hundred year old technologies that posses a very high power density compared with conventional capacitors. It can accept charge at high rate without degradation and can deliver power when needed [16]. Another advantage of ultracapacitor is that it is environment friendly. Ultracapacitor does not release any hazardous substance that can damage the environment as it does not contain any chemical substances.

2.3.1 Capacitance in Ultracapacitor

Ultracapacitor has a much higher capacitance than conventional capacitor because the inner surface of each electrode is not smooth and made of porous carbon, creating a very large surface area which about 100,000 times the surface area of a conventional capacitor with an extremely small separation distances of the electrodes.

By maximizing A and minimizing d in the Eq. (1), an ultracapacitor will achieve extremely high values of capacitance. Ultracapacitor and schematic of ultracapacitor are shown in Figure 2.7 and Figure 2.8 respectively.

In contrast to conventional capacitor which has only several microFarad (μF), its capacitance is measured in the value of Farads (F), and even approaching kiloFarad (kF) which can store a million times of the electrical energy [17].

Figure 2.7: Ultracapacitor

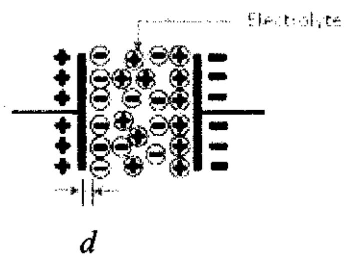

Figure 2.8: Schematic of ultracapacitor [23]

2.3.2 Temperature Effect on Ultracapacitor

Ultracapacitors are maintenance-free and perform well over a broad temperature range from -40°C to 85°C [21]. It is less affected by temperature than chemical reaction types. So the ultracapacitor can be used in lower temperatures, as they would function at temperatures as low as -25°C where lead batteries would fail [19].

Ultracapacitor cannot replace batteries completely; however they can be used to complement each other. In the hybrid electric vehicle, the ultracapacitor can be used during vehicle operation. Although battery cannot deliver large current at extremely low temperatures, it can deliver enough current current to slowly charge an ultracapacitor, which can be used to start the vehicle [20].

CHAPTER 3

METHODOLOGY

This chapter describes the work related to this project in details. There are five major parts in this chapter which are project activities flowchart, research methodology, Gantt Chart, tools and equipment required as well as circuit design.

3.1 Project Activities Flowchart

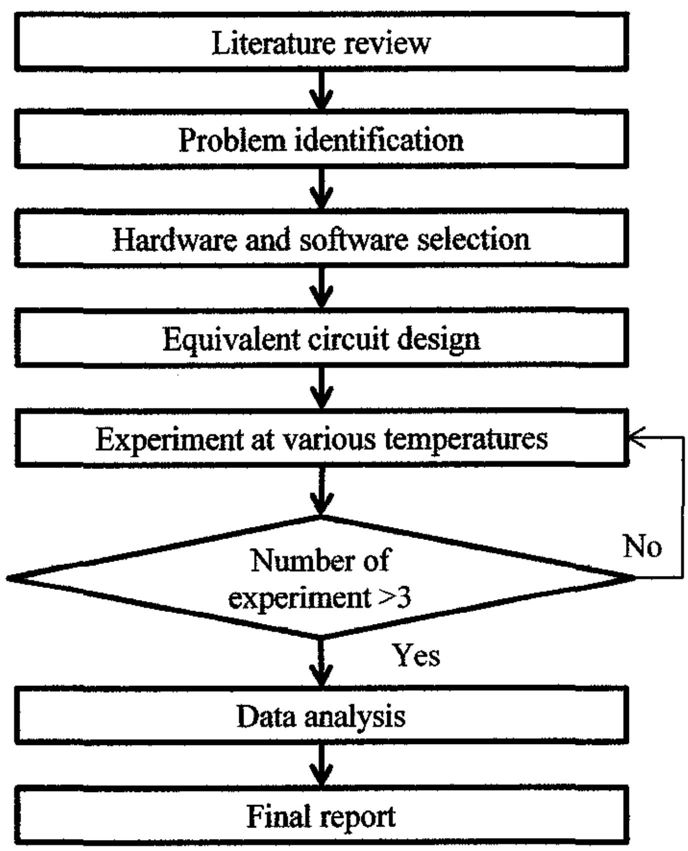

Figure 3.1: Project Activities Flowchart

Figure 3.1 shows the project activities flowchart of the project planning for FYP 1 and the continuation in FYP 2. This flowchart is very important to keep the project always on the track which will help the project finish on time. Those procedures for the implementation had to pass several steps. Each step had to finish before move on to another steps to make sure the project success.

3.2 Research Methodology

In order to achieve the objectives of this project, research is done with reference to several resources such as books, internet and technical papers to observe the possible solutions referring to the problem statements. Once approval has been obtained from the supervisor, the conceptual design is proposed according to the identified method of solution.

The experiment for this project is conducted in two stages; first stage is to design a circuit and second stage is to test the circuit at carious temperatures. NI Multisim software is used to design and verify circuit designs as well as to predict the behavior of the circuit. The equivalent circuit is then conducted using the breadboard. Then, the circuit is tested at various temperatures, so that the performance in different circuit equivalent could be compared. Experiments are performed to obtain the waveform of voltage and current across the load in battery, ultracapacitor and B-UC combination at various temperatures such as at -15℃, 10℃, 30℃, 50℃ and 70℃.

Figure 3.2 shows the experiment setup. A refrigerator is used to set up low temperatures; 10℃ and -15℃ (freezer) while an oven is to set up high temperatures; 30℃, 50℃ and 70℃. The refrigerator and oven are utilized to provide necessary control of the temperatures so that the effects of specific environmental conditions can be observed.

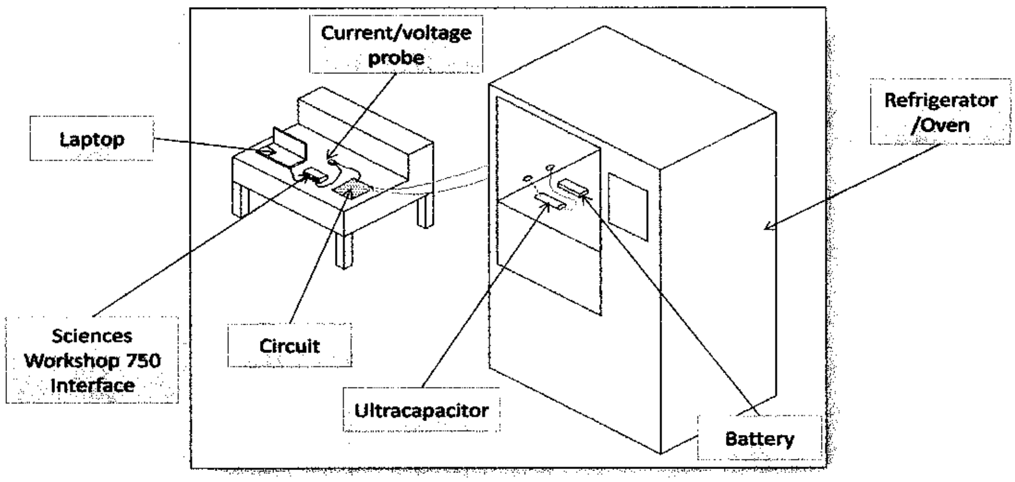

Figure 3.2: Experiment setup

This experiment has been done by putting battery and ultracapacitor continuously in a particular temperature for one hour. This is to ensure that the ultracapacitor and battery are in the stable temperatures so that any inconsistencies in temperature will not affect the results.

All parameters except temperature are set up to optimize reliability of results. Ultracapacitor is charged at 2.5 V throughout the experiment. Currents across load is collected from current sensors which is connected to ScienceWorkshop 750 Interface. Then, the DataStudio program will automatically plot the data into graphical display. The reliability of the experiment is improved by repeating the same experiment in temperature -15℃, 10℃, 30℃, 50℃ and 70℃ for three times. Results captured are analyzed thoroughly.

3.3 Gantt Chart

The Gantt chart is the dynamic guideline for the project timeline. It can be changed from time to time depending on certain circumstances. Below are the Gantt Chart for FYP 1 and FYP 2:

First Semester (FYP 1) Gantt Chart

Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
Selection and Confirmation of Project Topic															
Preliminary Research Work on Related Topic															
Submission of Extended Proposal						★									
Study on Battery and Ultracapacitor								Mid Semester Break							
Proposal Defence										★					
Circuit Design & Experiments															
Study & Analyze the result obtained.															
Submission of Interim Draft Report														★	
Submission of Interim Final Report															★

Second Semester (FYP 2) Gantt Chart

Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
Model Development & Modification Work															
Testing & Validation Work															
Submission of Progress Report									★						
Result Analysis & Discussion								Mid Semester Break							
ELEXTREX													★		
Submission of Draft Report														★	
Submission of Dissertation (soft bound)															★
Submission of Technical Paper															★
Oral Presentation															★
Submission of Project Dissertation (soft bound)															★

Legend: ☐ Process ★ Key Milestone

3.4 Tools and Equipment Required

Throughout the progress of this project, the suitable tools have been identified in order to complete this project. The tools are divided into two parts which are hardware and software.

3.4.1 Hardware

1. Battery

Dual AA battery size rated 1.5V and manufactured by Energizer is used as a power supply to the circuit model designed. The AA size battery is most commonly used in electrical appliances such as torchlight, mp3s, clocks, toys and remote control.

Figure 3.3: AA battery

2. Ultracapacitor

Ultracapacitor is classified as the energy electrical storage devices. Ultracapacitor with value 1F is used in this project. This ultracapacitor is manufactured by ELNA from USA. It also has 5.5V rated voltage as shown in Figure 3.4.

Figure 3.4: Ultracapacitor

3. Science Workshop 750 Interface

Science Workshop750 Interface as in the Figure 3.5 offer various of probe sensors to be used for data collection such as voltages, currents, lights, sounds, forces, motion, pH and etc.

Figure 3.5: ScienceWorkshop 750 interface

The ScienceWorkshop 750 Interface works as a connection medium between the sensor and the computer to display the experimental result. The current sensor as in Figure 3.6 is connected to the available port at the ScienceWorkshop 750 Interface and then the results are displayed in term of graph and table at the computer's screen. This current sensor is an analogue channel plug designed to interface to measure currents of ±1.5 amperes [21].

Figure 3.6: PASCO CI-6556 current sensor

. While for voltages recording, voltage sensor is to be used despite of a voltmeter. This sensor allows details monitoring of alternating current (AC) and DC voltage from –10 volts to +10 volts even as per mille second which will allow the accurate analysis. The probe ends are standard stackable banana plugs with detachable alligator clip adapters which will ease the connection to be made on particular circuit.

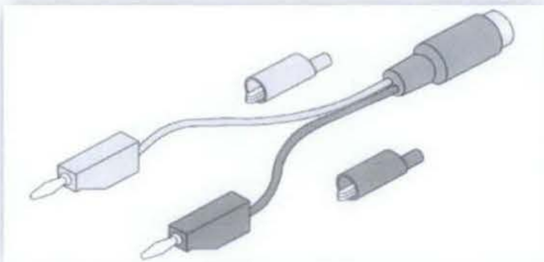

Figure 3.7: PASCO CI-6503 Voltage Sensor [21]

4. Light emitting diode (LED)

LED emits light when an electric current passes through it. The green color of LED with 2.2V forward voltage [16] is used as the DC load in the equivalent circuit. LED is connected in parallel to the power source and ultracapacitor. Figure 3.8 show the picture of LED in green color.

Figure 3.8: Light emitting diode [16]

5. Digital Multimeter

Multimeter measures electrical properties such as AC or DC voltage, current, and resistance. In this project, multimeter is used to determine the current across in the circuit as well as the maximum voltage supply to the ultracapacitor.

Figure 3.9: Digital multimeter

6. Refrigerator and Oven

Refrigerator (Figure 3.10) and oven (Figure 3.11) are used to keep the battery and ultracapacitor at low and high temperatures respectively for one hour. Refrigerator which included freezer give temperature from -15℃ to 10℃. Oven used in the chemical lab is set to be 30℃, 50℃ and 70℃.

Figure 3.10: Refrigerator

Figure 3.11: Oven

3.4.2 Software

1. National Instrument Multisim 11.0 (NI Multisim)

NI Multisim is an analog circuit and digital logic simulation software that runs on personal computers. This software is used in integrated circuit and board level design to check the integrity of circuit designs and to predict circuit behavior. The software used is the latest version NI Multisim 11.0 which is released on 2010. In comparison to PSPICE, there are more components available in Multisim which suit with the real component. For instance, ELDCs with the range of 1 to 5000 Farads is available in Multisim but in PSPICE only the conventional capacitors are available.

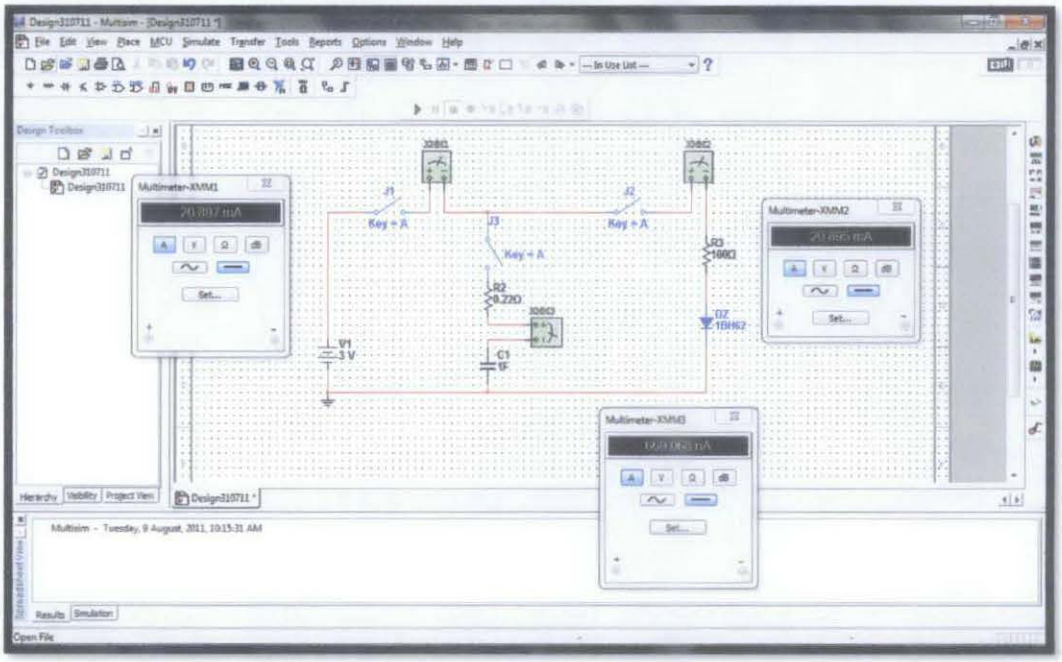

Figure 3.12: User Interface of NI Multisim Analog Devices Edition

2. Data Studio

Data Studio is a data acquisition, display and analysis program which is works with ScienceWorkshop 750 Interface. The data collected from ScienceWorkshop 750 Interface through current sensor will display, record and analyze onto Data Studio program. The data collected from the circuit will be automatically uploaded onto the DataStudio with graphical display and tabling display. The required setup and calibration between ScienceWorkshop 750 Interface and DataStudio Program has been studied as well as practical use of those hardware and software.

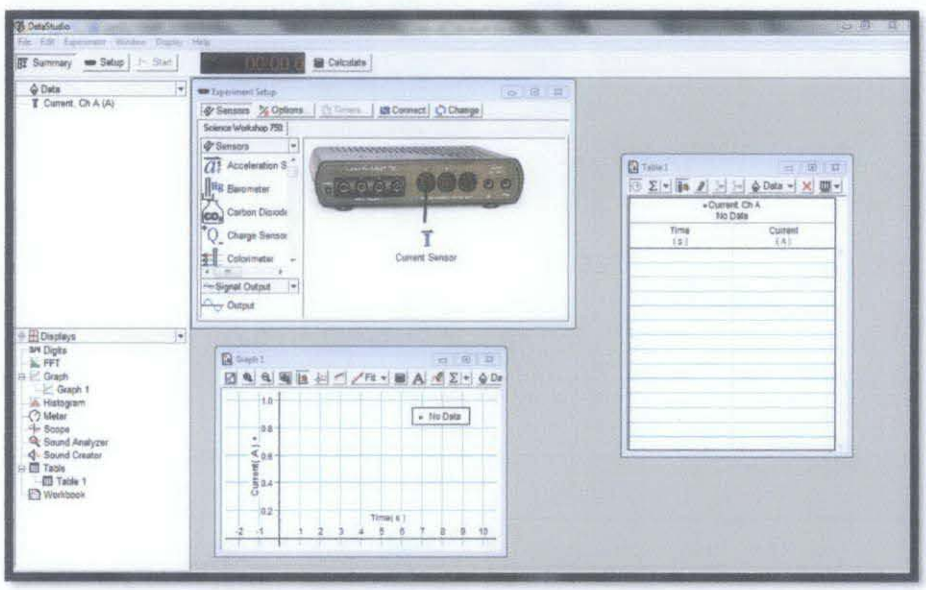

Figure 3.13: User Interface of Data Studio

3.5 Circuit Design

In this project, a circuit has been designed to run the experiments. This circuit consists of power sources, load, ultracapacitor and resistors, also known as resistor-capacitor (RC) circuit. The circuit is shown in Figure 3.14 as below:

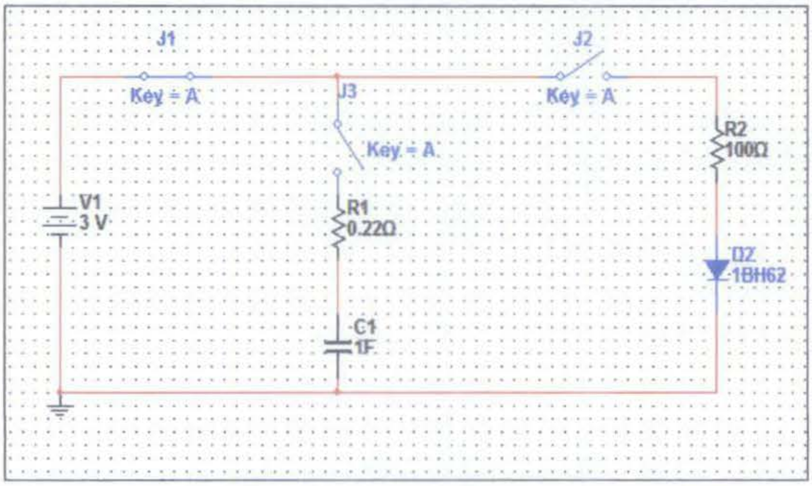

Figure 3.14: Circuit design

This circuit contains ultracapactior internal resistance noted as R1. This internal resistance obtained from the datasheet provided by the manufacturer of the ultracapacitor [26]. The internal reisistor R1 is connected in series with ultracapactor.

For LED (D2), 100 Ω (R2) is connected in series to limit the current through the LED, otherwise it will burn out almost instantly.
The resistor value, R2 is given by:

$$R2 = \frac{V_S - V_L}{I} \tag{3}$$

V_S = supply voltage (3V)

V_L = LED voltage (2V, for green LED) [22]

I = LED current (25mA = 0.025A for green LED) [22]

R2 = (3V - 2V) / 0.025A = 40 Ω

So resistor 100 Ω (the nearest standard value which is greater) is used in this circuit. If the calculated value is not available, the nearest standard resistor value which is greater is chosen, so that the current will be a little less than 25 mA. In fact choosing a greater resistor value to reduce the current but this will make the LED less bright [22].

Circuit Operation (Refer to Figure 3.14):

Switch J1	Switch J2	Switch J3	Output
Close	Close	Open	Battery (V1) is supplying current to the LED.
Close	Open	Close	V1 is charging the ultracapacitor (C1).
Open	Close	Close	C1 is supplying current to the LED.
Close	Close	Close	V1 is charging C1 and supplying current to the LED.

Electrical parameters used in the equivalent circuit model are:
Power supply V1: 3V
Ultracapacitor C1: 5.5V, 1.0F
Resistor R1: 0.22 ohms [23]
Resistor R2: 100 ohms
LED forward voltages at 25mA: ~2.2V

From this equivalent circuit, the waveform of the current across the load using battery, ultracapacitor and B-UC combination at temperatures -15℃, 10℃, 30℃, 50℃ and 70℃ can be obtained during the experiment.

3.5.1 RC Circuit

When a circuit consisting of a battery, a switch, a resistor and an ultracapacitor in a series loop is called an RC circuit. The ultracapacitor would have the same potential difference as the battery that charged it. Kirchoff's voltage law for this circuit is [24]:

$$V = IR + \frac{Q}{C} \qquad (4)$$

When expressed purely in terms of the charge, this becomes:

$$V = \frac{\mathrm{dQ}}{\mathrm{dt}} R + \frac{Q}{C} \tag{5}$$

When the switch is closed, the ultracapacitor charges over time:

$$Q = Q_f(1 - e^{-t/RC}) \tag{6}$$

Where Q is the charge at time t and Q_f is the final charge on the ultracapacitor. When the ultracapacitor is fully charged, the switch can be opened and (ideally) no charge will leak from the ultracapacitor. If the battery is removed and the switch closed, the ultracapacitor will then discharge over time [24]:

$$Q = Q_f e^{-t/RC} \tag{7}$$

CHAPTER 4

RESULTS & DISCUSSION

4.1 Data Gathering & Analysis

In this experiment, the result shows the data and graph of current which are obtained from the circuit that have been set up earlier. From this equivalent circuit, the waveform of the current across the load using battery, ultracapacitor and B-UC combination are obtained during the experiment at temperatures -15℃, 10℃, 30℃, 50℃ and 70℃.

Table below only shows the summary of the output current (A) waveform obtained from the experiment at temperatures -15℃, 10℃, 30℃, 50℃ and 70℃. The comparison of the result will be discussed further.

<u>At Temperature -15℃</u>

1. Current across load using battery

No. of reading (60 sec)	Trial (A)		
	1	2	3
1	0.889	0.887	0.860
2	0.889	0.887	0.860
3	0.888	0.887	0.860
4	0.888	0.887	0.860
5	0.888	0.887	0.860
Average (A)	**0.878**		

Table 4.1: Current across load using battery at temperature -15℃

2. Current across load using ultracapacitor

No. of reading (60sec)	Trial (A)		
	1	2	3
1	0.862	0.859	0.857
2	0.862	0.855	0.855
3	0.862	0.856	0.851
4	0.859	0.855	0.850
5	0.860	0.851	0.844
Average (A)	0.856		

Table 4.2: Current across load using ultracapacitor at temperature -15℃

3. Current across load using B-UC combination

No. of reading (60sec)	Trial (A)		
	1	2	3
1	0.863	0.886	0.859
2	0.868	0.886	0.859
3	0.869	0.886	0.859
4	0.870	0.886	0.860
5	0.871	0.886	0.861
Average (A)	0.871		

Table 4.3: Current across load using B-UC combination at temperature -15℃

At Temperature 10℃

1. Current across load using battery

No. of reading (60sec)	Trial (A)		
	1	2	3
1	0.912	0.907	0.907
2	0.912	0.907	0.907
3	0.912	0.907	0.907
4	0.912	0.907	0.907
5	0.912	0.907	0.908
Average (A)	0.909		

Table 4.4: Current across load using battery at temperature 10℃

2. Current across load using ultracapacitor

No. of reading (60sec)	Trial (A)		
	1	2	3
1	0.869	0.869	0.868
2	0.868	0.867	0.865
3	0.867	0.865	0.864
4	0.865	0.862	0.863
5	0.864	0.861	0.863
Average (A)	**0.865**		

Table 4.5: Current across load using ultracapacitor at temperature 10℃

3. Current across load using B-UC combination

No. of reading (60sec)	Trial (A)		
	1	2	3
1	0.907	0.906	0.906
2	0.910	0.906	0.907
3	0.911	0.907	0.907
4	0.912	0.907	0.907
5	0.912	0.907	0.907
Average (A)	**0.908**		

Table 4.6: Current across load using B-UC combination at temperature 10℃

At Temperature 30℃

1. Current across load using battery

No. of reading (60sec)	Trial (A)		
	1	2	3
1	0.909	0.911	0.909
2	0.909	0.911	0.909
3	0.909	0.911	0.909
4	0.909	0.911	0.909
5	0.909	0.911	0.909
Average (A)	**0.910**		

Table 4.7: Current across load using battery at temperature 30 ℃

2. Current across load using ultracapacitor

No. of reading (60sec)	Trial (A)		
	1	2	3
1	0.859	0.879	0.879
2	0.857	0.877	0.878
3	0.855	0.876	0.876
4	0.854	0.874	0.875
5	0.853	0.873	0.873
Average (A)	**0.869**		

Table 4.8: Current across load using ultracapacitor at temperature 30 ℃

3. Current across load using B-UC combination

No. of reading (60sec)	Trial (A)		
	1	2	3
1	0.908	0.911	0.908
2	0.908	0.911	0.908
3	0.908	0.911	0.908
4	0.908	0.911	0.908
5	0.908	0.911	0.908
Average (A)	**0.909**		

Table 4.9: Current across load using B-UC combination at temperature 30 ℃

At Temperature 50 ℃

1. Current across load using battery

No. of reading (60sec)	Trial (A)		
	1	2	3
1	0.908	0.908	0.903
2	0.908	0.906	0.903
3	0.909	0.906	0.902
4	0.907	0.907	0.902
5	0.909	0.907	0.902
Average (A)	**0.906**		

Table 4.10: Current across load using battery at temperature 50 ℃

2. Current across load using ultracapacitor

No. of reading (60sec)	Trial (A)		
	1	2	3
1	0.874	0.875	0.870
2	0.875	0.875	0.872
3	0.875	0.875	0.874
4	0.872	0.875	0.870
5	0.872	0.871	0.872
Average (A)	0.873		

Table 4.11: Current across load using ultracapacitor at temperature 50 ℃

3. Current across load using B-UC combination

No. of reading (60sec)	Trial (A)		
	1	2	3
1	0.893	0.897	0.885
2	0.898	0.902	0.890
3	0.901	0.905	0.891
4	0.903	0.901	0.897
5	0.905	0.904	0.902
Average (A)	0.898		

Table 4.12: Current across load using B-UC combination at temperature 50 ℃

<u>At Temperature 70 ℃</u>

1. Current across load using battery

No. of reading (60sec)	Trial (A)		
	1	2	3
1	0.898	0.897	0.896
2	0.898	0.896	0.896
3	0.897	0.896	0.896
4	0.897	0.897	0.896
5	0.898	0.897	0.896
Average (A)	0.897		

Table 4.13: Current across load using battery at temperature 70℃

2. Current across load using ultracapacitor

No. of reading (60sec)	Trial (A)		
	1	2	3
1	0.868	0.868	0.871
2	0.867	0.871	0.869
3	0.867	0.870	0.872
4	0.865	0.867	0.872
5	0.866	0.869	0.870
Average (A)	**0.869**		

Table 4.14: Current across load using ultracapacitor at temperature 70℃

3. Current across load using B-UC combination

No. of reading (60sec)	Trial (A)		
	1	2	3
1	0.893	0.888	0.884
2	0.896	0.894	0.887
3	0.898	0.896	0.891
4	0.898	0.897	0.896
5	0.899	0.897	0.898
Average (A)	**0.894**		

Table 4.15: Current across load using B-UC combination at temperature 70℃

Summary for the average current across load using battery, ultracapacitor and B-UC combination in every experiment is shown as below:

Temperatures (℃)	Current (*A*) across load using Battery	Current (*A*) across load using Ultracapacitor	Current (*A*) across load using B-UC combination
-15	0.879	0.856	0.871
10	0.909	0.865	0.908
30	0.910	0.869	0.909
50	0.906	0.873	0.898
70	0.897	0.869	0.894

Table 4.16: Summary of average current across load using battery and ultracapacitor

Figures 4.1-4.4 show the graphs generated from the results. Based on the average reading for every experiment, these are the graph for current across load using battery, ultracapacitor and B-UC combination at temperature -15℃, 10℃, 30℃, 50℃ and 70℃.

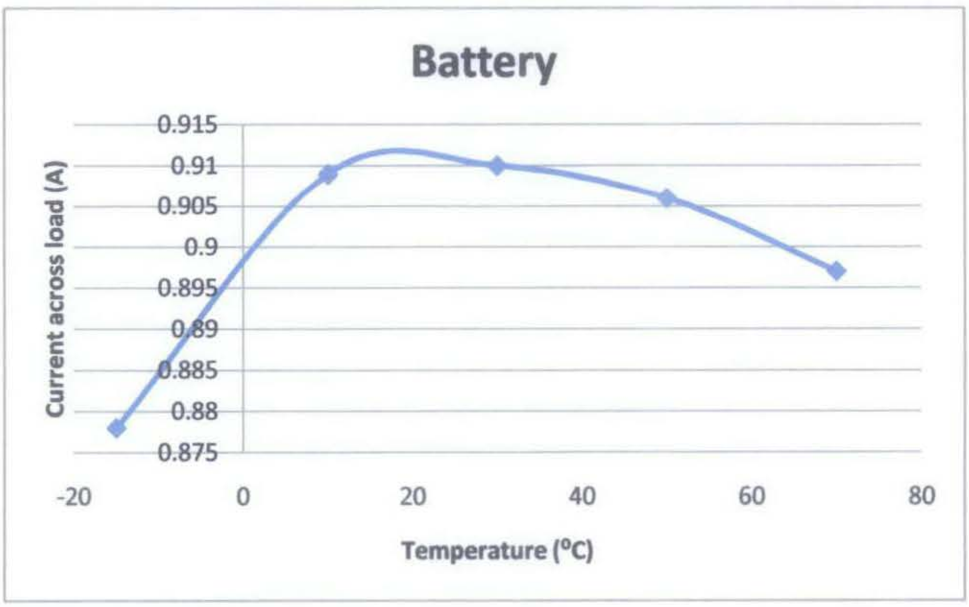

Figure 4.1: Graph of current across load (A) versus temperature (°C) for battery

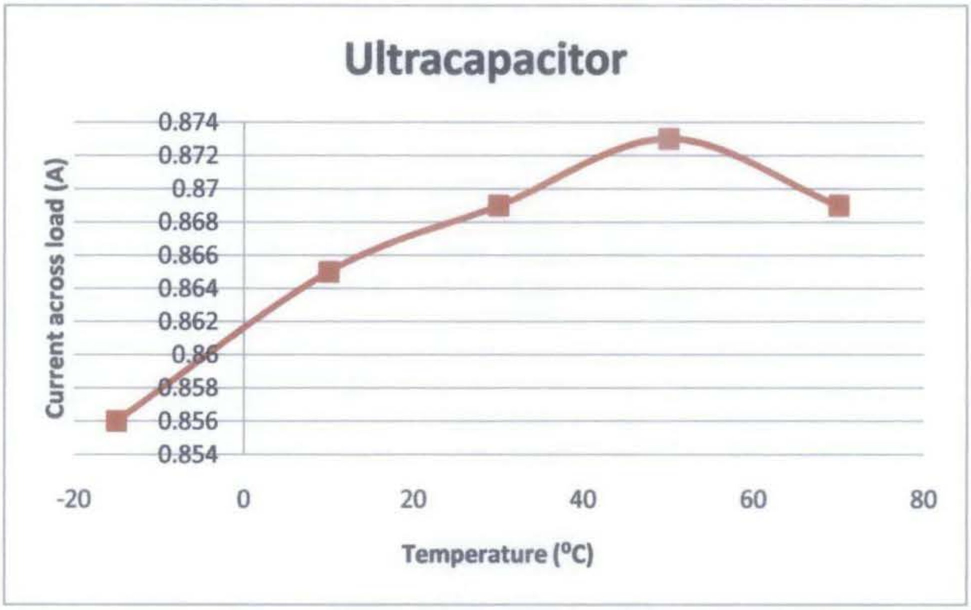

Figure 4.2: Graph of current across load (A) versus temperature (°C) for ultracapacitor

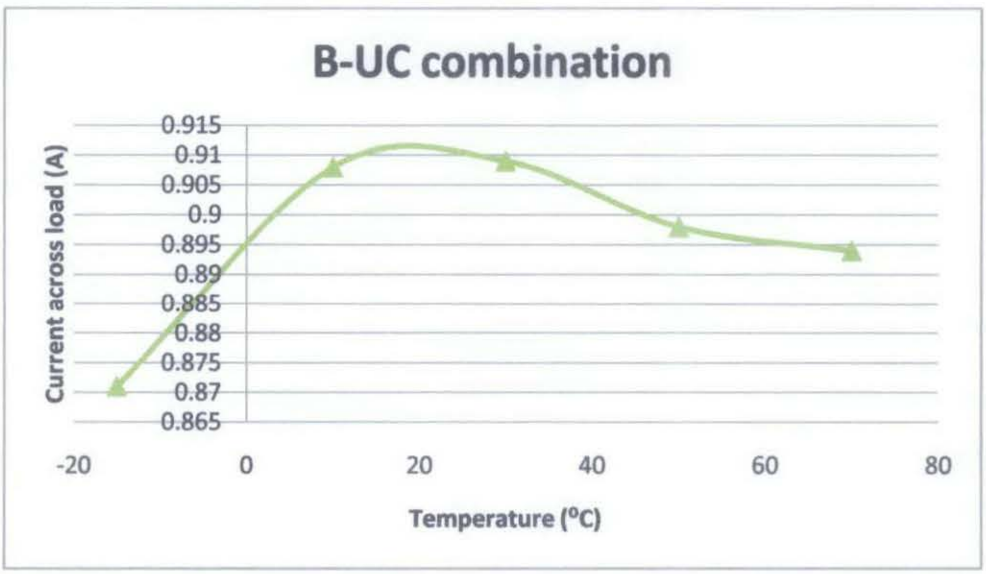

Figure 4.3: Graph of current across load (A) versus temperature (°C) for B-UC combination

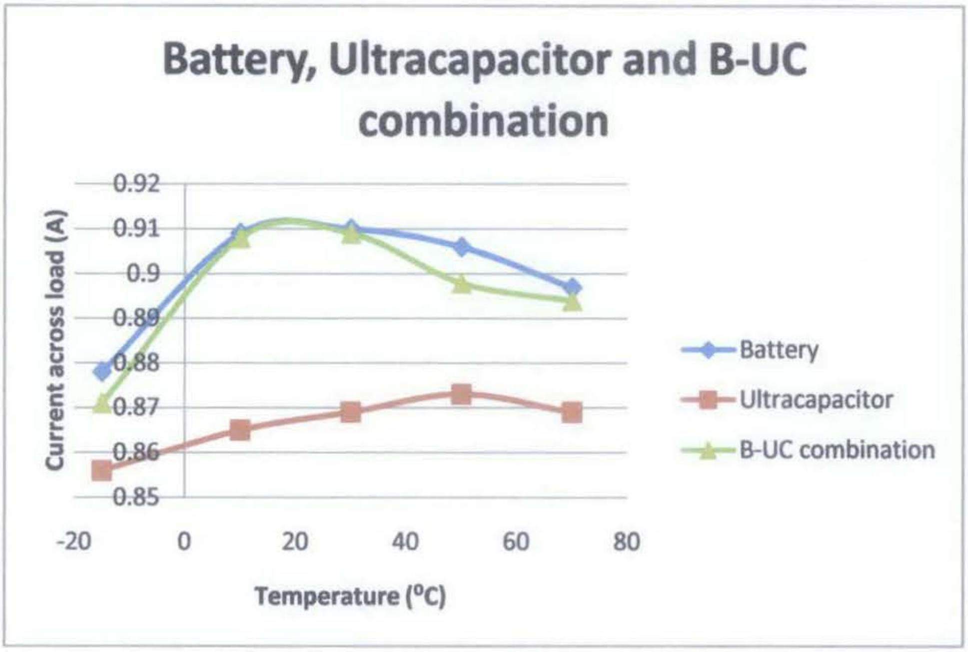

Figure 4.4: Graph of current across load (A) versus temperature (°C) for battery, ultracapacitor and B-UC combination

The rate of change from one temperature to another temperature is calculated. This is to show the performance of battery, ultracapacitor and B-UC combination at temperatures -15°C, 10°C, 30°C, 50°C and 70°C. Details follow:

Temperatures (℃)	Rate of change in battery (%)	Rate of change in ultracapacitor (%)	Rate of change in B-UC combination (%)
-15	3.41	1.50	4.18
10	3.41	1.05	4.25
30	0.10	0.46	0.11
50	0.44	0.46	1.21
70	1.00	0.46	0.45

Table 4.17: Rate of changes in battery, ultracapacitor and B-UC combination

Figures 4.5-4.8 show bar charts of rates of change in battery, ultracapacitor and B-UC combination generated from the data in Table 4.17.

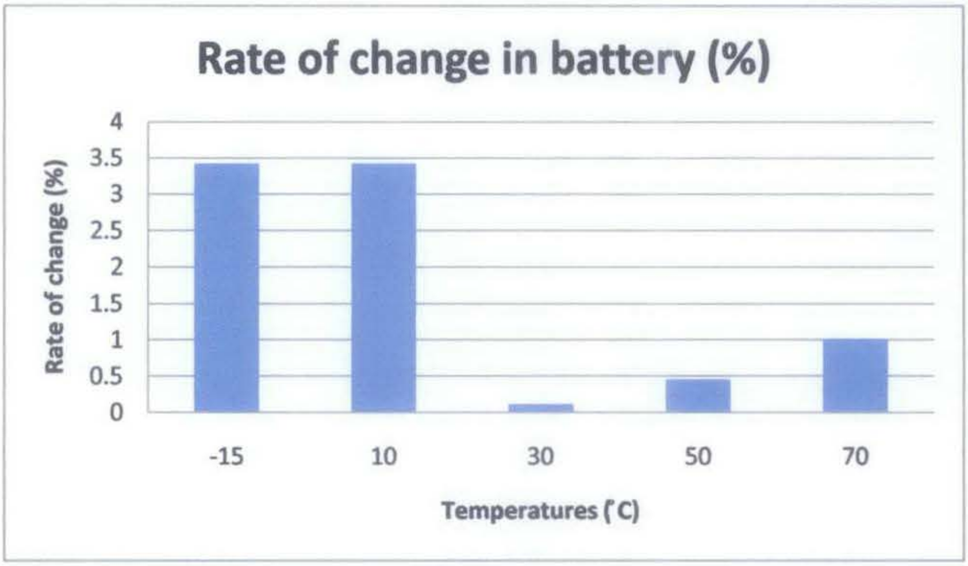

Figure 4.5: Rate of changes in battery

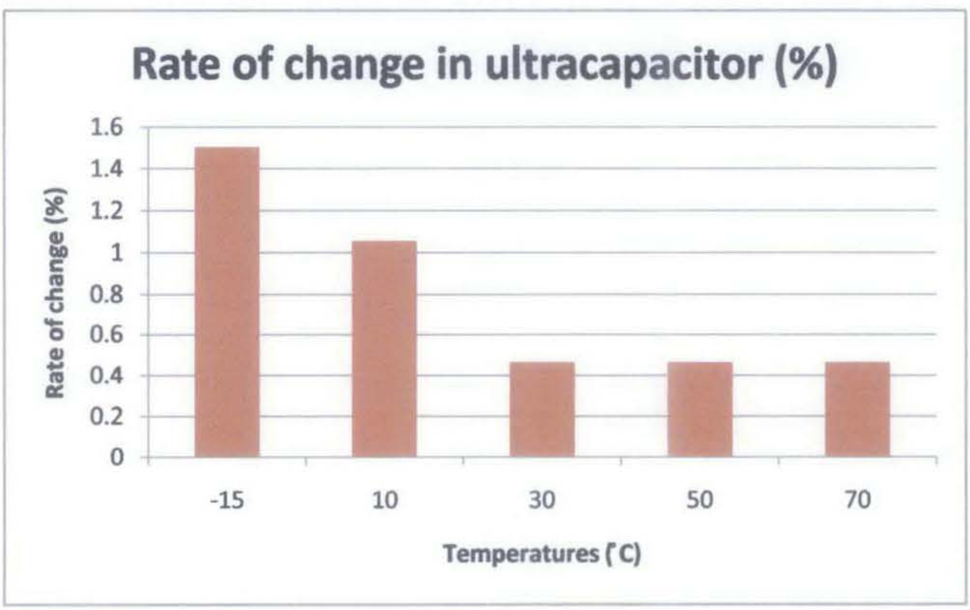

Figure 4.6: Rate of changes in ultracapacitor

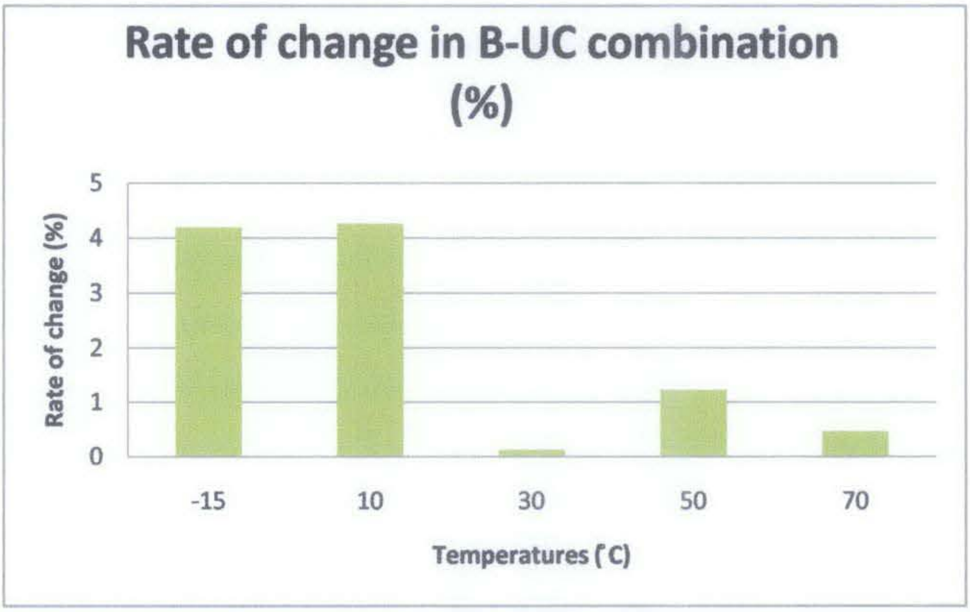

Figure 4.7: Rate of changes in B-UC combination

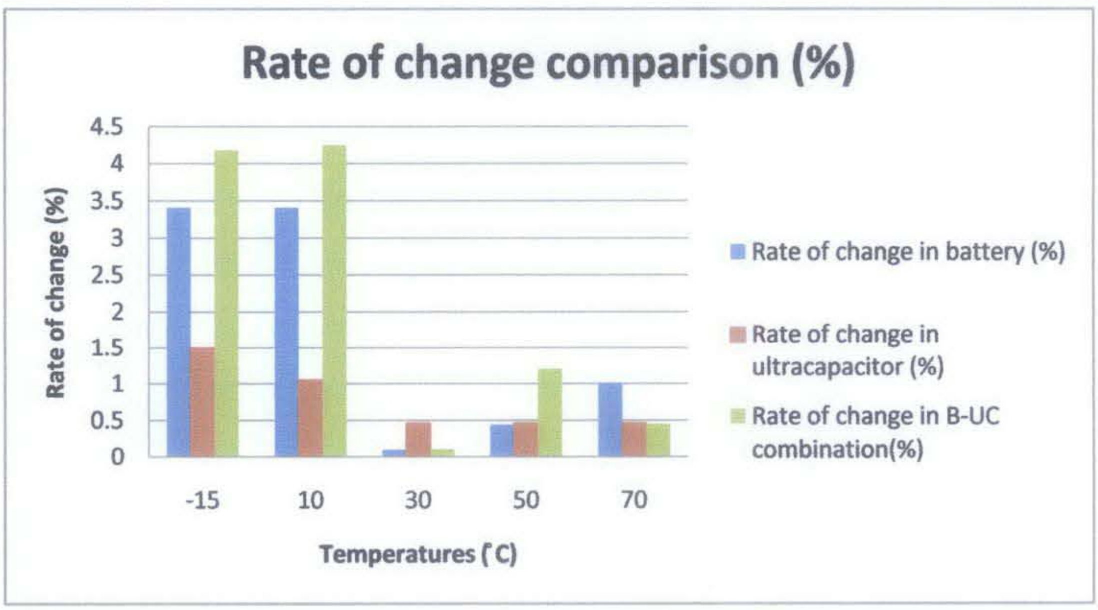

Figure 4.8: Rate of changes in battery, ultracapacitor and B-UC combination

4.2 Discussion

According to the results, the discussion can be made by comparing the performance of battery, ultracapacitor and B-UC combination supplying current across load at different temperatures. The average of every reading of current across the load is calculated using the formula:

$$Average = \frac{\sum Current\ across\ load\ (A)}{Number\ of\ readings} \qquad (8)$$

While the percentage rate of change (r) of the current across load at battery and ultracapacitor is calculated by:

$$Percentage\ of\ rate\ of\ change = \frac{A_{T2} - A_{T1}}{A_{T1}} \times 100\% \qquad (9)$$

Where A_{T1} = Current across load at initial temperature

A_{T2} = Current across load at final temperature

Referring to Table 4.17, current across the load is regarded "stable" if there is not much change from one temperature to one temperature. It can be classified as follow:

Stable	$0 \leq r \leq 1.5$
Less stable	$1.5 \leq r \leq 3$
Not stable	$r \geq 3$

Table 4.18: Classification

<u>Current across Load Using Battery</u>

Details below demonstrate the rate of change of the battery with the classification as mention in Table 4.18.

Temperatures (℃)	Rate of change in battery (%)	Classification
-15	3.41	Not stable
10	3.41	Not stable
30	0.10	Stable
50	0.44	Stable
70	1.00	Stable

Table 4.19: Rate of change in battery

This result proves that battery operates less efficiently at lower temperature. From 30°C to 70°C, the current across load is not having much changes compared at low temperature which only. These indicate that the performance of the battery is much stable at higher temperature.

The results from this research is consistence with those found on [3] that as the chemical reaction in the battery is temperature dependent, the chemical reaction in battery slows down at low temperature and causing the voltage drop. Thus, the current supply by the battery at low temperature will be decreased. Chemical reactions in the battery are driven either by voltage or temperature. The hotter the battery, the faster chemical reactions. The performance of the battery increases with high temperature, but at the same time the rate of the unwanted chemical reactions will increase resulting in a corresponding loss of battery life. Literature review as already explained in [2].

Current across Load Using Ultracapacitor

Details below demonstrate the rate of change of the ultracapacitor with the classification as mention in Table 4.18.

Temperatures (℃)	Rate of change in ultracapacitor (%)	Classification
-15	1.50	Stable
10	1.05	Stable
30	0.46	Stable
50	0.46	Stable
70	0.46	Stable

Table 4.20: Rate of change in ultracapacitor

The rate of change of the ultracapacitor is smaller than the battery at most of the temperatures. It indicates that ultracapacitor is stable at low or high temperature. The value of the current keep decreasing in Trial 1, 2, and 3 is because the ultracapacitor which is kept in refrigerator or oven for one hour is being discharged. Since there are no complicated chemical reactions taking place in a ultracapacitor during normal operation, its performance remains completely unaffected over a very wide range of temperatures from -40°C to 85°C.

<u>Current across Load Using B-UC combination</u>

Details below demonstrate the rate of change of the B-UC combination with the classification as mention in Table 4.18.

Temperatures (℃)	Rate of change inB-UC combination (%)	Classification
-15	4.18	Not stable
10	4.25	Not stable
30	0.11	Stable
50	1.21	Stable
70	0.45	Stable

Table 4.21: Rate of change in B-UC combination

Referring to the result, the performance of the B-UC combination is not stable at low temperature and stable at high temperature. The rate of change in this equivalent circuit is quite big compared to battery and ultracapacitor standalone especially during cold temperatures because of the charging method which affect the current supply from the battery to the load. The period of getting the reading is also only 60s which is only time for charging the ultracapacitor itself.

Although the rate of changes is higher than battery and ultracapacitor standalone, the B-UC combination equivalent circuit could provide less battery internal power losses which improve the battery current output in the equivalent circuit. This characteristic is important to the devices or vehicle so it could endure in high or low temperature without degrading the performance (in term of power burst and life cycle).

Other than that, by putting battery together with ultracapacitor, it will lower the ESR of the battery which contributed to the better current performance than the circuit without the ultracapacitor especially during cold weather. Although battery cannot deliver large current at extremely low temperatures, the battery can deliver enough current to gradually charge an ultracapacitor, which can be used to start vehicle or other electronic. This may suggest the use of longer lasting battery rather than large battery designed to deliver hundreds of ampere during start cold.

CHAPTER 5

CONCLUSION & RECOMMENDATION

5.1 Conclusion

In conclusion, a complete circuit of a working prototype using ultrcapacitor and battery as the power supply was experimentally done. The effect of ultracapacitor on the battery performance to provide enough current to the load at five different temperatures temperatures (-15℃, 10℃ and 30℃, 50℃, 70℃) has been investigated. From the experiments, at low temperature (from -15℃ to 10℃), the performance of ultracapacitor is more stable compared to battery and B-UC combination. At high temperature (30℃ to 70℃), the performance of the ultracapacitor, battery and B-UC combination are stable. However, the performance of ultracapacitor is more stable than battery and B-UC combination which only involve 0.46% rate of changes. The performance of the ultracapacitor is very stable for all the temperatures tested and will not affect the devices when used for a long period even at high temperatures. The battery performance is insufficient because it has to be replaced frequently as it will no longer hold a charge after use. Ultracapacitor definitely cannot replace batteries completely; however they are able to complement each other. When battery combines with ultracapacitor, overall system performance will improve and battery life also will extend.

5.2 Limitation

An important tool for this study is a temperature chamber which was not available on campus. More reliable results could be obtained if a temperature chamber is used.

5.3 Recommendation

Throughout the project, some factors and problems encountered have been identified which affect the results and giving delay onto this project. A few modifications and improvements should be taken for the future work. Some of those modifications and improvements are:-

- Veroboard is recommended to install the electrical parameters to get more precise result for a better connection. The characteristic of the breadboard contribute to the loose connection of the electrical parameter such as batteries, ultracapacitor and jumper wire which affected the final result from the experiment.

- To overcome reading inaccuracies of digital multimeter, voltage regulator can be used to specify amount of voltage so that ultracapacitor is being charged in constantly at the beginning of the experiment.

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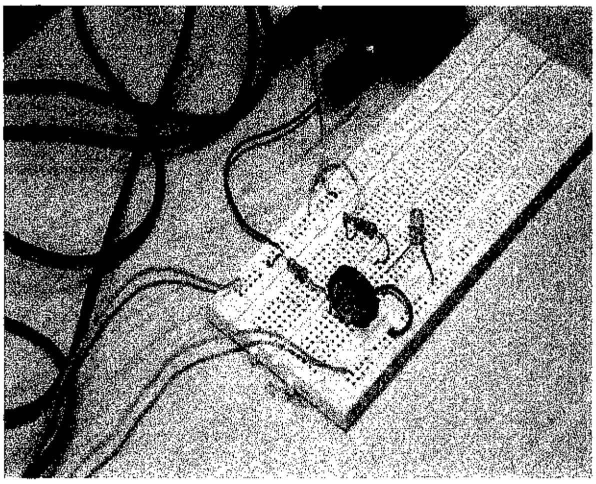
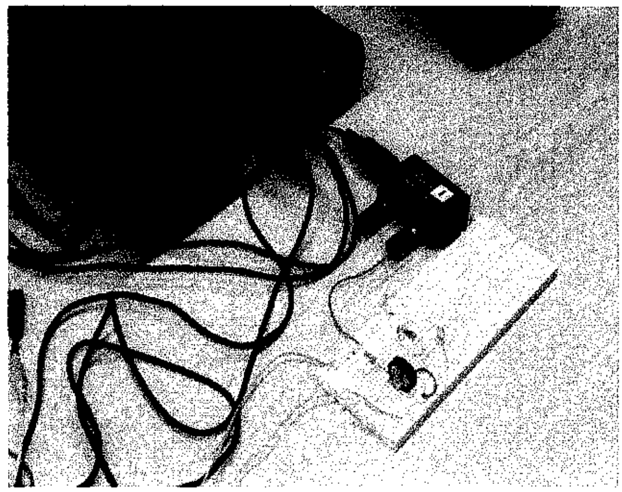
APPENDICES

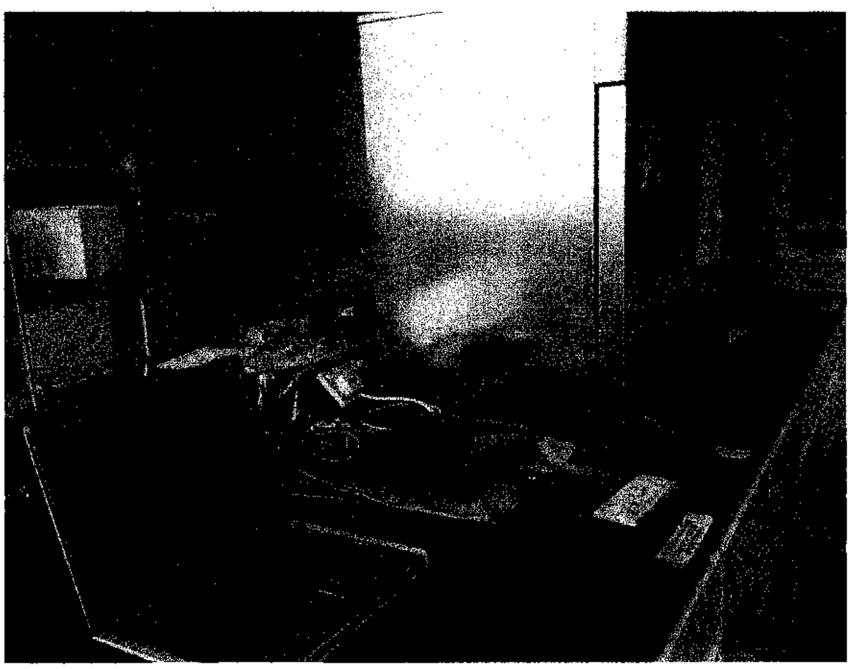
PROTOYPE FOR THE PROJECT



Circuit Design

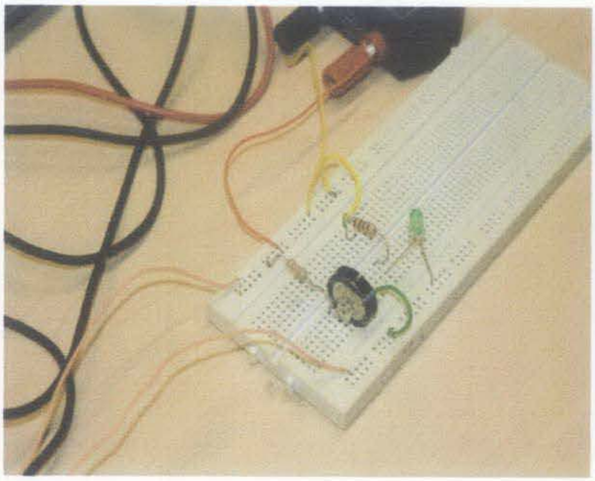


Connection to PASCO

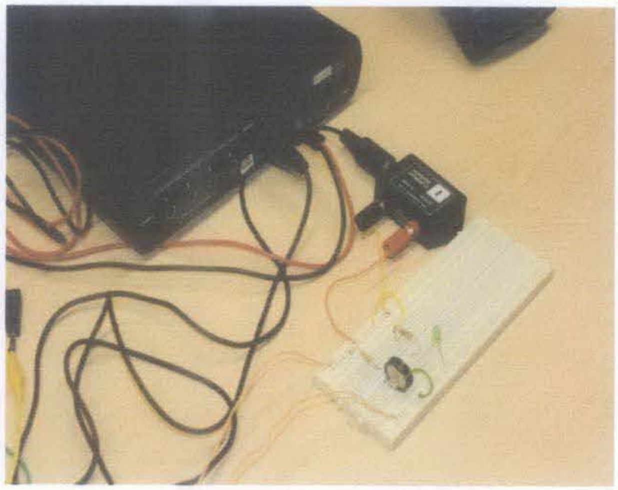


Workstation

PROTOYPE FOR THE PROJECT



Circuit Design



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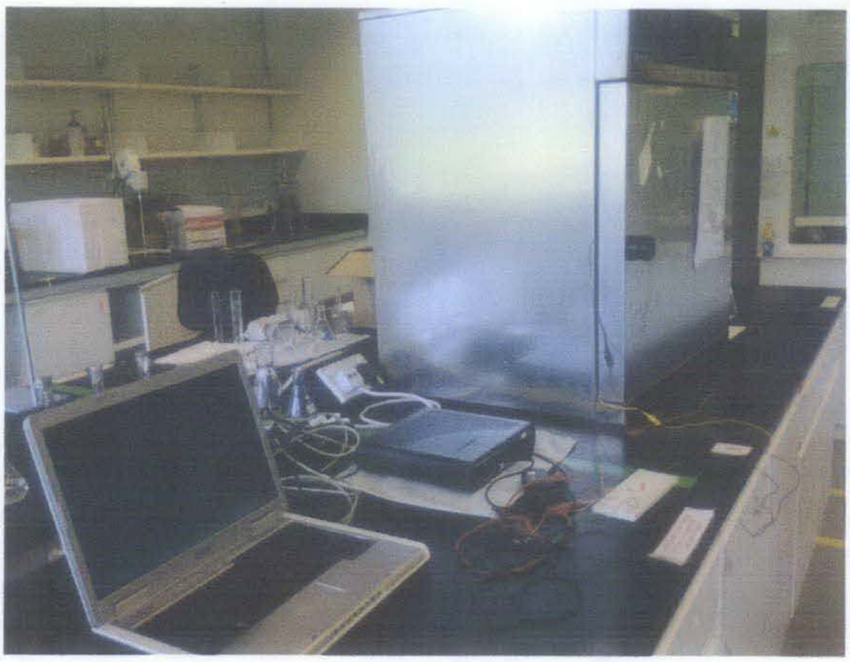

Workstation

DATA GAINED FROM THE EXPERIMENT

At temperature -15 (battery)

Current, Ch A Run #7		Current, Ch A Run #8		Current, Ch A Run #9		Current, Ch A Run #10		Current, Ch A Run #11	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.4000	0.888	59.4000	0.889	59.4000	0.888	59.4000	0.890	59.4000	0.889
59.5000	0.888	59.5000	0.890	59.5000	0.888	59.5000	0.889	59.5000	0.889
59.6000	0.888	59.6000	0.889	59.6000	0.888	59.6000	0.889	59.6000	0.889
59.7000	0.888	59.7000	0.890	59.7000	0.888	59.7000	0.889	59.7000	0.889
59.8000	0.888	59.8000	0.889	59.8000	0.888	59.8000	0.889	59.8000	0.889
59.9000	0.888	59.9000	0.890	59.9000	0.888	59.9000	0.889	59.9000	0.889
60.0000	0.888	60.0000	0.888	60.0000	0.888	60.0000	0.889	60.0000	0.889
Minimum	0.888	Minimum	0.888	Minimum	0.888	Minimum	0.888	Minimum	0.888
Maximum	0.893	Maximum	0.895	Maximum	0.892	Maximum	0.891	Maximum	0.890
Mean	0.889	Mean	0.889	Mean	0.888	Mean	0.888	Mean	0.888

Trial 1

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.4000	0.887	59.4000	0.888	59.4000	0.887	59.4000	0.887	59.4000	0.887
59.5000	0.886	59.5000	0.889	59.5000	0.887	59.5000	0.887	59.5000	0.887
59.6000	0.887	59.6000	0.888	59.6000	0.887	59.6000	0.887	59.6000	0.887
59.7000	0.887	59.7000	0.888	59.7000	0.887	59.7000	0.887	59.7000	0.887
59.8000	0.887	59.8000	0.887	59.8000	0.887	59.8000	0.887	59.8000	0.887
59.9000	0.887	59.9000	0.888	59.9000	0.887	59.9000	0.887	59.9000	0.887
60.0000	0.887	60.0000	0.888	60.0000	0.887	60.0000	0.887	60.0000	0.887
Minimum	0.886	Minimum	0.886	Minimum	0.886	Minimum	0.887	Minimum	0.886
Maximum	0.888	Maximum	0.889	Maximum	0.889	Maximum	0.888	Maximum	0.887
Mean	0.887	Mean	0.887	Mean	0.887	Mean	0.887	Mean	0.887

Trial 2

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.4000	0.860	59.4000	0.860	59.4000	0.860	59.4000	0.860	59.4000	0.860
59.5000	0.860	59.5000	0.860	59.5000	0.860	59.5000	0.860	59.5000	0.860
59.6000	0.860	59.6000	0.860	59.6000	0.860	59.6000	0.860	59.6000	0.860
59.7000	0.860	59.7000	0.860	59.7000	0.860	59.7000	0.860	59.7000	0.860
59.8000	0.860	59.8000	0.860	59.8000	0.860	59.8000	0.860	59.8000	0.860
59.9000	0.860	59.9000	0.860	59.9000	0.860	59.9000	0.860	59.9000	0.860
60.0000	0.860	60.0000	0.860	60.0000	0.860	60.0000	0.860	60.0000	0.860
Minimum	0.859	Minimum	0.859	Minimum	0.859	Minimum	0.860	Minimum	0.860
Maximum	0.861	Maximum	0.861	Maximum	0.860	Maximum	0.861	Maximum	0.861
Mean	0.860	Mean	0.860	Mean	0.860	Mean	0.860	Mean	0.860

Trial 3

At temperature -15 (ultracapacitor)

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #6	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.4000	0.863	59.4000	0.868	59.4000	0.863	59.4000	0.859	59.4000	0.865
59.5000	0.863	59.5000	0.869	59.5000	0.863	59.5000	0.859	59.5000	0.866
59.6000	0.863	59.6000	0.869	59.6000	0.862	59.6000	0.859	59.6000	0.868
59.7000	0.863	59.7000	0.869	59.7000	0.862	59.7000	0.860	59.7000	0.868
59.8000	0.863	59.8000	0.868	59.8000	0.863	59.8000	0.862	59.8000	0.868
59.9000	0.863	59.9000	0.869	59.9000	0.863	59.9000	0.865	59.9000	0.868
60.0000	0.863	60.0000	0.869	60.0000	0.863	60.0000	0.866	60.0000	0.868
Minimum	0.853	Minimum	0.852	Minimum	0.854	Minimum	0.848	Minimum	0.845
Maximum	0.872	Maximum	0.871	Maximum	0.873	Maximum	0.872	Maximum	0.873
Mean	0.862	Mean	0.862	Mean	0.862	Mean	0.859	Mean	0.860

Trial 1

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
58.9000	0.858	58.9000	0.853	58.9000	0.860	58.9000	0.864	58.9000	0.850
59.0000	0.857	59.0000	0.853	59.0000	0.859	59.0000	0.864	59.0000	0.850
59.1000	0.857	59.1000	0.853	59.1000	0.858	59.1000	0.864	59.1000	0.850
59.2000	0.857	59.2000	0.853	59.2000	0.858	59.2000	0.864	59.2000	0.850
59.3000	0.858	59.3000	0.853	59.3000	0.858	59.3000	0.864	59.3000	0.850
59.4000	0.857	59.4000	0.852	59.4000	0.859	59.4000	0.864	59.4000	0.850
59.5000	0.857	59.5000	0.852	59.5000	0.860	59.5000	0.863	59.5000	0.850
Minimum	0.846	Minimum	0.845	Minimum	0.843	Minimum	0.842	Minimum	0.841
Maximum	0.868	Maximum	0.867	Maximum	0.866	Maximum	0.865	Maximum	0.863
Mean	0.859	Mean	0.855	Mean	0.856	Mean	0.855	Mean	0.851

Trial 2

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.4000	0.856	59.4000	0.854	59.4000	0.850	59.4000	0.849	59.4000	0.844
59.5000	0.856	59.5000	0.854	59.5000	0.850	59.5000	0.849	59.5000	0.844
59.6000	0.856	59.6000	0.854	59.6000	0.850	59.6000	0.849	59.6000	0.844
59.7000	0.856	59.7000	0.854	59.7000	0.850	59.7000	0.849	59.7000	0.844
59.8000	0.856	59.8000	0.854	59.8000	0.850	59.8000	0.849	59.8000	0.844
59.9000	0.856	59.9000	0.854	59.9000	0.850	59.9000	0.849	59.9000	0.844
60.0000	0.856	60.0000	0.855	60.0000	0.850	60.0000	0.849	60.0000	0.844
Minimum	0.856	Minimum	0.854	Minimum	0.850	Minimum	0.849	Minimum	0.843
Maximum	0.859	Maximum	0.856	Maximum	0.853	Maximum	0.850	Maximum	0.845
Mean	0.857	Mean	0.855	Mean	0.851	Mean	0.850	Mean	0.844

Trial 3

At temperature -15 (B-UC combination)

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.4000	0.864	59.4000	0.868	59.4000	0.869	59.4000	0.870	59.4000	0.871
59.5000	0.865	59.5000	0.869	59.5000	0.869	59.5000	0.870	59.5000	0.871
59.6000	0.864	59.6000	0.868	59.6000	0.869	59.6000	0.870	59.6000	0.871
59.7000	0.864	59.7000	0.869	59.7000	0.869	59.7000	0.870	59.7000	0.871
59.8000	0.864	59.8000	0.868	59.8000	0.869	59.8000	0.870	59.8000	0.871
59.9000	0.864	59.9000	0.868	59.9000	0.869	59.9000	0.870	59.9000	0.871
60.0000	0.864	60.0000	0.868	60.0000	0.869	60.0000	0.870	60.0000	0.871
Minimum	0.862	Minimum	0.867	Minimum	0.869	Minimum	0.869	Minimum	0.870
Maximum	0.865	Maximum	0.869	Maximum	0.870	Maximum	0.870	Maximum	0.871
Mean	0.863	Mean	0.868	Mean	0.869	Mean	0.870	Mean	0.871

Trial 1

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.4000	0.886	59.4000	0.886	59.4000	0.886	59.4000	0.886	59.4000	0.886
59.5000	0.886	59.5000	0.886	59.5000	0.886	59.5000	0.886	59.5000	0.886
59.6000	0.886	59.6000	0.886	59.6000	0.886	59.6000	0.886	59.6000	0.886
59.7000	0.886	59.7000	0.886	59.7000	0.886	59.7000	0.886	59.7000	0.886
59.8000	0.886	59.8000	0.886	59.8000	0.886	59.8000	0.886	59.8000	0.886
59.9000	0.886	59.9000	0.886	59.9000	0.886	59.9000	0.886	59.9000	0.886
60.0000	0.886	60.0000	0.886	60.0000	0.886	60.0000	0.886	60.0000	0.886
Minimum	0.886	Minimum	0.886	Minimum	0.886	Minimum	0.886	Minimum	0.886
Maximum	0.886	Maximum	0.886	Maximum	0.886	Maximum	0.886	Maximum	0.887
Mean	0.886	Mean	0.886	Mean	0.886	Mean	0.886	Mean	0.886

Trial 2

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.4000	0.861	59.4000	0.860	59.4000	0.860	59.4000	0.860	59.4000	0.861
59.5000	0.860	59.5000	0.860	59.5000	0.860	59.5000	0.860	59.5000	0.861
59.6000	0.860	59.6000	0.860	59.6000	0.860	59.6000	0.860	59.6000	0.861
59.7000	0.861	59.7000	0.860	59.7000	0.860	59.7000	0.860	59.7000	0.861
59.8000	0.861	59.8000	0.860	59.8000	0.860	59.8000	0.860	59.8000	0.862
59.9000	0.861	59.9000	0.860	59.9000	0.860	59.9000	0.860	59.9000	0.861
60.0000	0.861	60.0000	0.860	60.0000	0.860	60.0000	0.860	60.0000	0.861
Minimum	0.842	Minimum	0.843	Minimum	0.844	Minimum	0.860	Minimum	0.860
Maximum	0.861	Maximum	0.860	Maximum	0.860	Maximum	0.860	Maximum	0.862
Mean	0.859	Mean	0.859	Mean	0.859	Mean	0.860	Mean	0.861

Trial 3

At temperature 10 (battery)

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.4000	0.912	59.4000	0.912	59.4000	0.911	59.4000	0.912	59.4000	0.912
59.5000	0.912	59.5000	0.912	59.5000	0.912	59.5000	0.911	59.5000	0.911
59.6000	0.912	59.6000	0.912	59.6000	0.911	59.6000	0.912	59.6000	0.912
59.7000	0.912	59.7000	0.912	59.7000	0.911	59.7000	0.912	59.7000	0.912
59.8000	0.912	59.8000	0.912	59.8000	0.912	59.8000	0.911	59.8000	0.912
59.9000	0.912	59.9000	0.912	59.9000	0.911	59.9000	0.912	59.9000	0.912
60.0000	0.912	60.0000	0.912	60.0000	0.912	60.0000	0.912	60.0000	0.912
Minimun	0.911	Minimun	0.911	Minimun	0.911	Minimun	0.911	Minimun	0.911
Maximur	0.912	Maximur	0.913	Maximur	0.912	Maximur	0.913	Maximur	0.912
Mean	0.912	Mean	0.912	Mean	0.912	Mean	0.911	Mean	0.912

Trial 1

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
58.8000	0.907	58.8000	0.907	58.8000	0.907	58.8000	0.907	58.8000	0.907
58.9000	0.907	58.9000	0.907	58.9000	0.907	58.9000	0.907	58.9000	0.907
59.0000	0.907	59.0000	0.907	59.0000	0.907	59.0000	0.907	59.0000	0.907
59.1000	0.907	59.1000	0.907	59.1000	0.907	59.1000	0.907	59.1000	0.907
59.2000	0.907	59.2000	0.907	59.2000	0.907	59.2000	0.907	59.2000	0.907
59.3000	0.907	59.3000	0.907	59.3000	0.907	59.3000	0.907	59.3000	0.907
59.4000	0.907	59.4000	0.907	59.4000	0.907	59.4000	0.907	59.4000	0.907
Minimum	0.907	Minimum	0.904	Minimum	0.906	Minimum	0.906	Minimum	0.906
Maximum	0.911	Maximum	0.907	Maximum	0.907	Maximum	0.907	Maximum	0.907
Mean	0.907	Mean	0.907	Mean	0.907	Mean	0.907	Mean	0.907

Trial 2

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
58.8000	0.907	58.8000	0.907	58.8000	0.908	58.8000	0.907	58.8000	0.908
58.9000	0.907	58.9000	0.907	58.9000	0.908	58.9000	0.907	58.9000	0.908
59.0000	0.907	59.0000	0.907	59.0000	0.908	59.0000	0.907	59.0000	0.908
59.1000	0.907	59.1000	0.907	59.1000	0.908	59.1000	0.907	59.1000	0.908
59.2000	0.907	59.2000	0.907	59.2000	0.908	59.2000	0.907	59.2000	0.908
59.3000	0.907	59.3000	0.907	59.3000	0.908	59.3000	0.907	59.3000	0.908
59.4000	0.907	59.4000	0.907	59.4000	0.908	59.4000	0.907	59.4000	0.908
Minimum	0.907	Minimum	0.907	Minimum	0.907	Minimum	0.907	Minimum	0.907
Maximum	0.908	Maximum	0.908	Maximum	0.908	Maximum	0.908	Maximum	0.908
Mean	0.907	Mean	0.907	Mean	0.907	Mean	0.907	Mean	0.908

Trial 3

At temperature 10 (ultracapacitor)

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.4000	0.869	59.4000	0.867	59.4000	0.866	59.4000	0.865	59.4000	0.863
59.5000	0.869	59.5000	0.867	59.5000	0.866	59.5000	0.865	59.5000	0.863
59.6000	0.869	59.6000	0.867	59.6000	0.866	59.6000	0.865	59.6000	0.863
59.7000	0.869	59.7000	0.867	59.7000	0.866	59.7000	0.865	59.7000	0.863
59.8000	0.869	59.8000	0.867	59.8000	0.866	59.8000	0.865	59.8000	0.863
59.9000	0.869	59.9000	0.867	59.9000	0.866	59.9000	0.865	59.9000	0.863
60.0000	0.869	60.0000	0.867	60.0000	0.866	60.0000	0.865	60.0000	0.863
Minimum	0.869	Minimum	0.867	Minimum	0.866	Minimum	0.865	Minimum	0.863
Maximum	0.870	Maximum	0.869	Maximum	0.867	Maximum	0.866	Maximum	0.865
Mean	0.869	Mean	0.868	Mean	0.867	Mean	0.865	Mean	0.864

Trial 1

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.4000	0.868	59.4000	0.866	59.4000	0.864	59.4000	0.861	59.4000	0.861
59.5000	0.868	59.5000	0.866	59.5000	0.864	59.5000	0.861	59.5000	0.861
59.6000	0.868	59.6000	0.866	59.6000	0.864	59.6000	0.861	59.6000	0.860
59.7000	0.868	59.7000	0.866	59.7000	0.864	59.7000	0.862	59.7000	0.861
59.8000	0.868	59.8000	0.866	59.8000	0.864	59.8000	0.862	59.8000	0.860
59.9000	0.868	59.9000	0.866	59.9000	0.864	59.9000	0.861	59.9000	0.861
60.0000	0.868	60.0000	0.866	60.0000	0.864	60.0000	0.862	60.0000	0.861
Minimum	0.868	Minimum	0.866	Minimum	0.864	Minimum	0.861	Minimum	0.860
Maximum	0.871	Maximum	0.868	Maximum	0.866	Maximum	0.864	Maximum	0.861
Mean	0.869	Mean	0.867	Mean	0.865	Mean	0.862	Mean	0.861

Trial 2

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
58.9000	0.868	58.9000	0.863	58.9000	0.864	58.9000	0.863	58.9000	0.862
59.0000	0.868	59.0000	0.863	59.0000	0.864	59.0000	0.864	59.0000	0.862
59.1000	0.868	59.1000	0.863	59.1000	0.864	59.1000	0.864	59.1000	0.862
59.2000	0.868	59.2000	0.863	59.2000	0.864	59.2000	0.864	59.2000	0.862
59.3000	0.868	59.3000	0.863	59.3000	0.864	59.3000	0.864	59.3000	0.862
59.4000	0.867	59.4000	0.863	59.4000	0.864	59.4000	0.864	59.4000	0.862
59.5000	0.868	59.5000	0.863	59.5000	0.864	59.5000	0.864	59.5000	0.862
Minimum	0.867	Minimum	0.863	Minimum	0.860	Minimum	0.863	Minimum	0.862
Maximum	0.870	Maximum	0.866	Maximum	0.865	Maximum	0.865	Maximum	0.864
Mean	0.868	Mean	0.865	Mean	0.863	Mean	0.864	Mean	0.863

Trial 3

At temperature 10 (B-UC combination)

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.4000	0.912	59.4000	0.912	59.4000	0.911	59.4000	0.912	59.4000	0.911
59.5000	0.912	59.5000	0.912	59.5000	0.911	59.5000	0.911	59.5000	0.912
59.6000	0.912	59.6000	0.912	59.6000	0.911	59.6000	0.912	59.6000	0.911
59.7000	0.912	59.7000	0.912	59.7000	0.911	59.7000	0.912	59.7000	0.911
59.8000	0.912	59.8000	0.912	59.8000	0.911	59.8000	0.912	59.8000	0.912
59.9000	0.912	59.9000	0.912	59.9000	0.911	59.9000	0.912	59.9000	0.911
60.0000	0.912	60.0000	0.912	60.0000	0.911	60.0000	0.912	60.0000	0.912
Minimum	-0.016	Minimum	0.873	Minimum	0.911	Minimum	0.911	Minimum	0.911
Maximum	0.913	Maximum	0.912	Maximum	0.912	Maximum	0.912	Maximum	0.912
Mean	0.907	Mean	0.910	Mean	0.911	Mean	0.912	Mean	0.912

Trial 1

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
58.4000	0.907	58.4000	0.907	58.4000	0.907	58.4000	0.907	58.4000	0.907
58.5000	0.906	58.5000	0.907	58.5000	0.907	58.5000	0.907	58.5000	0.907
58.6000	0.907	58.6000	0.907	58.6000	0.907	58.6000	0.907	58.6000	0.907
58.7000	0.907	58.7000	0.907	58.7000	0.907	58.7000	0.907	58.7000	0.907
58.8000	0.907	58.8000	0.907	58.8000	0.907	58.8000	0.907	58.8000	0.907
58.9000	0.907	58.9000	0.907	58.9000	0.907	58.9000	0.907	58.9000	0.907
59.0000	0.907	59.0000	0.907	59.0000	0.907	59.0000	0.907	59.0000	0.907
Minimum	0.862	Minimum	0.871	Minimum	0.906	Minimum	0.906	Minimum	0.907
Maximum	0.907	Maximum	0.907	Maximum	0.907	Maximum	0.907	Maximum	0.907
Mean	0.906	Mean	0.906	Mean	0.907	Mean	0.907	Mean	0.907

Trial 2

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
58.9000	0.907	58.9000	0.907	58.9000	0.907	58.9000	0.907	58.9000	0.906
59.0000	0.907	59.0000	0.907	59.0000	0.907	59.0000	0.907	59.0000	0.906
59.1000	0.907	59.1000	0.907	59.1000	0.907	59.1000	0.907	59.1000	0.906
59.2000	0.907	59.2000	0.907	59.2000	0.907	59.2000	0.907	59.2000	0.906
59.3000	0.907	59.3000	0.907	59.3000	0.907	59.3000	0.907	59.3000	0.906
59.4000	0.907	59.4000	0.907	59.4000	0.906	59.4000	0.907	59.4000	0.906
59.5000	0.907	59.5000	0.907	59.5000	0.907	59.5000	0.907	59.5000	0.906
Minimum	7.874E-3	Minimum	0.906	Minimum	0.906	Minimum	0.906	Minimum	0.906
Maximum	0.908	Maximum	0.908	Maximum	0.908	Maximum	0.907	Maximum	0.907
Mean	0.906	Mean	0.907	Mean	0.907	Mean	0.907	Mean	0.907

Trial 3

At temperature 30 (battery)

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #5		Current, Ch A Run #4	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
58.8000	0.909	58.8000	0.909	58.8000	0.909	58.8000	0.909	58.8000	0.909
58.9000	0.909	58.9000	0.909	58.9000	0.909	58.9000	0.909	58.9000	0.909
59.0000	0.909	59.0000	0.909	59.0000	0.909	59.0000	0.909	59.0000	0.909
59.1000	0.909	59.1000	0.909	59.1000	0.909	59.1000	0.909	59.1000	0.909
59.2000	0.909	59.2000	0.909	59.2000	0.909	59.2000	0.909	59.2000	0.909
59.3000	0.909	59.3000	0.909	59.3000	0.909	59.3000	0.909	59.3000	0.909
59.4000	0.909	59.4000	0.909	59.4000	0.909	59.4000	0.909	59.4000	0.909
Minimum	0.908	Minimum	0.908	Minimum	0.909	Minimum	0.909	Minimum	0.909
Maximum	0.909	Maximum	0.909	Maximum	0.909	Maximum	0.909	Maximum	0.909
Mean	0.909	Mean	0.909	Mean	0.909	Mean	0.909	Mean	0.909

Trial 1

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
58.9000	0.911	58.9000	0.911	58.9000	0.911	58.9000	0.911	58.9000	0.911
59.0000	0.911	59.0000	0.911	59.0000	0.911	59.0000	0.911	59.0000	0.911
59.1000	0.911	59.1000	0.911	59.1000	0.911	59.1000	0.911	59.1000	0.911
59.2000	0.911	59.2000	0.911	59.2000	0.911	59.2000	0.911	59.2000	0.911
59.3000	0.911	59.3000	0.911	59.3000	0.911	59.3000	0.911	59.3000	0.911
59.4000	0.911	59.4000	0.911	59.4000	0.911	59.4000	0.911	59.4000	0.911
59.5000	0.911	59.5000	0.911	59.5000	0.911	59.5000	0.911	59.5000	0.911
Minimum	0.910	Minimum	0.911	Minimum	0.911	Minimum	0.911	Minimum	0.911
Maximum	0.911	Maximum	0.911	Maximum	0.911	Maximum	0.911	Maximum	0.911
Mean	0.911	Mean	0.911	Mean	0.911	Mean	0.911	Mean	0.911

Trial 2

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.0000	0.908	59.0000	0.908	59.0000	0.909	59.0000	0.908	59.0000	0.909
59.1000	0.909	59.1000	0.909	59.1000	0.909	59.1000	0.908	59.1000	0.908
59.2000	0.909	59.2000	0.908	59.2000	0.909	59.2000	0.908	59.2000	0.908
59.3000	0.909	59.3000	0.908	59.3000	0.909	59.3000	0.908	59.3000	0.909
59.4000	0.909	59.4000	0.908	59.4000	0.909	59.4000	0.908	59.4000	0.909
59.5000	0.909	59.5000	0.909	59.5000	0.909	59.5000	0.908	59.5000	0.909
59.6000	0.909	59.6000	0.909	59.6000	0.909	59.6000	0.909	59.6000	0.908
Minimum	0.908	Minimum	0.908	Minimum	0.908	Minimum	0.908	Minimum	0.908
Maximum	0.909	Maximum	0.909	Maximum	0.909	Maximum	0.909	Maximum	0.910
Mean	0.909	Mean	0.909	Mean	0.909	Mean	0.908	Mean	0.908

Trial 3

At temperature 30 (ultracapacitor)

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
0.0000	0.860	0.0000	0.858	0.0000	0.857	0.0000	0.855	0.0000	0.855
0.1000	0.860	0.1000	0.859	0.1000	0.856	0.1000	0.855	0.1000	0.854
0.2000	0.860	0.2000	0.858	0.2000	0.856	0.2000	0.855	0.2000	0.854
0.3000	0.860	0.3000	0.858	0.3000	0.856	0.3000	0.855	0.3000	0.854
0.4000	0.860	0.4000	0.858	0.4000	0.856	0.4000	0.855	0.4000	0.854
0.5000	0.860	0.5000	0.858	0.5000	0.857	0.5000	0.855	0.5000	0.854
0.6000	0.860	0.6000	0.858	0.6000	0.856	0.6000	0.855	0.6000	0.854
Minimum	0.858	Minimum	0.856	Minimum	0.854	Minimum	0.853	Minimum	0.852
Maximum	0.860	Maximum	0.859	Maximum	0.857	Maximum	0.855	Maximum	0.856
Mean	0.859	Mean	0.857	Mean	0.855	Mean	0.854	Mean	0.853

Trial 1

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.0000	0.878	59.0000	0.876	59.0000	0.875	59.0000	0.873	59.0000	0.872
59.1000	0.878	59.1000	0.876	59.1000	0.875	59.1000	0.873	59.1000	0.872
59.2000	0.878	59.2000	0.876	59.2000	0.875	59.2000	0.873	59.2000	0.872
59.3000	0.878	59.3000	0.876	59.3000	0.875	59.3000	0.873	59.3000	0.872
59.4000	0.878	59.4000	0.876	59.4000	0.875	59.4000	0.873	59.4000	0.872
59.5000	0.878	59.5000	0.876	59.5000	0.875	59.5000	0.873	59.5000	0.872
59.6000	0.878	59.6000	0.876	59.6000	0.875	59.6000	0.873	59.6000	0.872
Minimum	0.878	Minimum	0.876	Minimum	0.875	Minimum	0.873	Minimum	0.872
Maximum	0.880	Maximum	0.878	Maximum	0.876	Maximum	0.875	Maximum	0.873
Mean	0.879	Mean	0.877	Mean	0.876	Mean	0.874	Mean	0.872

Trial 2

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
57.9000	0.878	57.9000	0.877	57.9000	0.876	57.9000	0.874	57.9000	0.872
58.0000	0.879	58.0000	0.877	58.0000	0.875	58.0000	0.874	58.0000	0.872
58.1000	0.879	58.1000	0.877	58.1000	0.875	58.1000	0.874	58.1000	0.872
58.2000	0.879	58.2000	0.877	58.2000	0.875	58.2000	0.874	58.2000	0.872
58.3000	0.879	58.3000	0.877	58.3000	0.875	58.3000	0.874	58.3000	0.872
58.4000	0.879	58.4000	0.877	58.4000	0.875	58.4000	0.874	58.4000	0.872
58.5000	0.879	58.5000	0.877	58.5000	0.876	58.5000	0.874	58.5000	0.872
Minimum	0.878	Minimum	0.877	Minimum	0.875	Minimum	0.874	Minimum	0.872
Maximum	0.881	Maximum	0.879	Maximum	0.877	Maximum	0.876	Maximum	0.874
Mean	0.879	Mean	0.878	Mean	0.876	Mean	0.875	Mean	0.873

Trial 3

At temperature 30 (B-UC combination)

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
58.7000	0.908	58.7000	0.908	58.7000	0.908	58.7000	0.908	58.7000	0.909
58.8000	0.908	58.8000	0.908	58.8000	0.908	58.8000	0.908	58.8000	0.909
58.9000	0.908	58.9000	0.908	58.9000	0.908	58.9000	0.908	58.9000	0.909
59.0000	0.908	59.0000	0.908	59.0000	0.908	59.0000	0.908	59.0000	0.909
59.1000	0.908	59.1000	0.908	59.1000	0.908	59.1000	0.908	59.1000	0.909
59.2000	0.908	59.2000	0.908	59.2000	0.909	59.2000	0.908	59.2000	0.908
59.3000	0.908	59.3000	0.908	59.3000	0.908	59.3000	0.908	59.3000	0.908
Minimum	0.908	Minimum	0.908	Minimum	0.908	Minimum	0.908	Minimum	0.908
Maximum	0.909	Maximum	0.909	Maximum	0.909	Maximum	0.909	Maximum	0.909
Mean	0.908	Mean	0.908	Mean	0.908	Mean	0.908	Mean	0.909

Trial 1

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.1000	0.911	59.1000	0.911	59.1000	0.911	59.1000	0.910	59.1000	0.911
59.2000	0.911	59.2000	0.911	59.2000	0.911	59.2000	0.911	59.2000	0.911
59.3000	0.911	59.3000	0.911	59.3000	0.911	59.3000	0.910	59.3000	0.911
59.4000	0.911	59.4000	0.911	59.4000	0.911	59.4000	0.911	59.4000	0.911
59.5000	0.911	59.5000	0.911	59.5000	0.911	59.5000	0.911	59.5000	0.911
59.6000	0.911	59.6000	0.911	59.6000	0.911	59.6000	0.911	59.6000	0.911
59.7000	0.911	59.7000	0.911	59.7000	0.911	59.7000	0.911	59.7000	0.911
Minimum	0.910	Minimum	0.910	Minimum	0.911	Minimum	0.910	Minimum	0.910
Maximum	0.911	Maximum	0.911	Maximum	0.911	Maximum	0.911	Maximum	0.911
Mean	0.911	Mean	0.911	Mean	0.811	Mean	0.911	Mean	0.911

Trial 2

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
57.9000	0.908	57.9000	0.908	57.9000	0.908	57.9000	0.908	57.9000	0.908
58.0000	0.908	58.0000	0.908	58.0000	0.908	58.0000	0.908	58.0000	0.908
58.1000	0.908	58.1000	0.908	58.1000	0.908	58.1000	0.908	58.1000	0.908
58.2000	0.909	58.2000	0.908	58.2000	0.908	58.2000	0.908	58.2000	0.908
58.3000	0.908	58.3000	0.908	58.3000	0.908	58.3000	0.908	58.3000	0.908
58.4000	0.908	58.4000	0.908	58.4000	0.908	58.4000	0.908	58.4000	0.908
58.5000	0.908	58.5000	0.908	58.5000	0.908	58.5000	0.908	58.5000	0.908
Minimum	0.908	Minimum	0.908	Minimum	0.908	Minimum	0.908	Minimum	0.908
Maximum	0.910	Maximum	0.910	Maximum	0.909	Maximum	0.909	Maximum	0.908
Mean	0.908	Mean	0.908	Mean	0.908	Mean	0.908	Mean	0.908

Trial 3

At temperature 50 (battery)

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.0000	0.908	59.0000	0.908	59.0000	0.910	59.0000	0.910	59.0000	0.910
59.1000	0.908	59.1000	0.908	59.1000	0.910	59.1000	0.910	59.1000	0.910
59.2000	0.908	59.2000	0.908	59.2000	0.910	59.2000	0.910	59.2000	0.910
59.3000	0.908	59.3000	0.908	59.3000	0.910	59.3000	0.910	59.3000	0.910
59.4000	0.908	59.4000	0.908	59.4000	0.910	59.4000	0.910	59.4000	0.910
59.5000	0.908	59.5000	0.908	59.5000	0.910	59.5000	0.909	59.5000	0.910
59.6000	0.908	59.6000	0.908	59.6000	0.910	59.6000	0.910	59.6000	0.910
Minimum	0.907	Minimum	0.907	Minimum	0.907	Minimum	0.889	Minimum	0.889
Maximum	0.908	Maximum	0.908	Maximum	0.910	Maximum	0.910	Maximum	0.910
Mean	0.908	Mean	0.908	Mean	0.909	Mean	0.907	Mean	0.909

Trial 1

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.5000	0.908	59.5000	0.906	59.5000	0.906	59.5000	0.907	59.5000	0.908
59.6000	0.908	59.6000	0.906	59.6000	0.906	59.6000	0.907	59.6000	0.908
59.7000	0.908	59.7000	0.906	59.7000	0.906	59.7000	0.907	59.7000	0.908
59.8000	0.908	59.8000	0.906	59.8000	0.906	59.8000	0.907	59.8000	0.908
59.9000	0.908	59.9000	0.906	59.9000	0.906	59.9000	0.907	59.9000	0.908
60.0000	0.908	60.0000	0.906	60.0000	0.906	60.0000	0.907	60.0000	0.908
Minimum	0.907	Minimum	0.905	Minimum	0.905	Minimum	0.906	Minimum	0.907
Maximum	0.908	Maximum	0.908	Maximum	[illegible]	Maximum	0.907	Maximum	0.908
Mean	0.908	Mean	0.906	Mean	0.906	Mean	0.907	Mean	0.907

Trial 2

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
58.5000	0.903	58.5000	0.902	58.5000	0.902	58.5000	0.902	58.5000	0.902
58.6000	0.903	58.6000	0.902	58.6000	0.902	58.6000	0.902	58.6000	0.902
58.7000	0.903	58.7000	0.902	58.7000	0.902	58.7000	0.902	58.7000	0.902
58.8000	0.903	58.8000	0.902	58.8000	0.902	58.8000	0.902	58.8000	0.902
58.9000	0.903	58.9000	0.902	58.9000	0.902	58.9000	0.902	58.9000	0.959
59.0000	0.903	59.0000	0.902	59.0000	0.902	59.0000	0.902	59.0000	0.902
59.1000	0.903	59.1000	0.902	59.1000	0.902	59.1000	0.902	59.1000	0.902
Minimum	0.903	Minimum	[illegible]	Minimum	0.902	Minimum	0.902	Minimum	0.902
Maximum	0.938	Maximum	[illegible]	Maximum	0.906	Maximum	0.902	Maximum	0.960
Mean	0.903	Mean	[illegible]	Mean	0.902	Mean	0.902	Mean	0.902

Trial 3

At temperature 50 (ultracapacitor)

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.4000	0.875	59.4000	0.859	59.4000	0.874	59.4000	0.872	59.4000	0.870
59.5000	0.874	59.5000	0.858	59.5000	0.874	59.5000	0.870	59.5000	0.870
59.6000	0.873	59.6000	0.858	59.6000	0.874	59.6000	0.869	59.6000	0.871
59.7000	0.872	59.7000	0.858	59.7000	0.873	59.7000	0.869	59.7000	0.870
59.8000	0.872	59.8000	0.858	59.8000	0.873	59.8000	0.869	59.8000	0.870
59.9000	0.872	59.9000	0.858	59.9000	0.873	59.9000	0.868	59.9000	0.870
60.0000	0.872	60.0000	0.858	60.0000	0.873	60.0000	0.869	60.0000	0.870
Minimum	0.854	Minimum	0.858	Minimum	0.856	Minimum	0.856	Minimum	0.854
Maximum	0.876	Maximum	0.876	Maximum	0.876	Maximum	0.874	Maximum	0.874
Mean	0.866	Mean	0.867	Mean	0.867	Mean	0.865	Mean	0.866

Trial 1

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.4000	0.876	59.4000	0.870	59.4000	0.875	59.4000	0.864	59.4000	0.865
59.5000	0.876	59.5000	0.870	59.5000	0.874	59.5000	0.866	59.5000	0.865
59.6000	0.876	59.6000	0.870	59.6000	0.874	59.6000	0.867	59.6000	0.866
59.7000	0.876	59.7000	0.870	59.7000	0.874	59.7000	0.867	59.7000	0.866
59.8000	0.876	59.8000	0.870	59.8000	0.873	59.8000	0.867	59.8000	0.867
59.9000	0.876	59.9000	0.870	59.9000	0.873	59.9000	0.867	59.9000	0.866
60.0000	0.877	60.0000	0.870	60.0000	0.873	60.0000	0.867	60.0000	0.866
Minimum	0.858	Minimum	0.861	Minimum	0.860	Minimum	0.859	Minimum	0.853
Maximum	0.878	Maximum	0.880	Maximum	0.878	Maximum	0.879	Maximum	0.891
Mean	0.868	Mean	0.871	Mean	0.870	Mean	0.867	Mean	0.869

Trial 2

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.4000	0.861	59.4000	0.860	59.4000	0.881	59.4000	0.881	59.4000	0.874
59.5000	0.861	59.5000	0.860	59.5000	0.882	59.5000	0.881	59.5000	0.873
59.6000	0.861	59.6000	0.860	59.6000	0.882	59.6000	0.879	59.6000	0.872
59.7000	0.861	59.7000	0.861	59.7000	0.882	59.7000	0.878	59.7000	0.871
59.8000	0.861	59.8000	0.862	59.8000	0.882	59.8000	0.878	59.8000	0.871
59.9000	0.861	59.9000	0.862	59.9000	0.882	59.9000	0.878	59.9000	0.872
60.0000	0.861	60.0000	0.862	60.0000	0.882	60.0000	0.878	60.0000	0.872
Minimum	0.858	Minimum	0.858	Minimum	0.859	Minimum	0.855	Minimum	0.858
Maximum	0.882	Maximum	0.882	Maximum	0.885	Maximum	0.887	Maximum	0.891
Mean	0.871	Mean	0.869	Mean	0.872	Mean	0.872	Mean	0.870

Trial 3

At temperature 50 (B-UC combination)

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.0000	0.896	59.0000	0.900	59.0000	0.902	59.0000	0.904	59.0000	0.905
59.1000	0.896	59.1000	0.899	59.1000	0.902	59.1000	0.904	59.1000	0.905
59.2000	0.896	59.2000	0.900	59.2000	0.902	59.2000	0.904	59.2000	0.906
59.3000	0.896	59.3000	0.900	59.3000	0.902	59.3000	0.904	59.3000	0.906
59.4000	0.896	59.4000	0.899	59.4000	0.902	59.4000	0.904	59.4000	0.906
59.5000	0.896	59.5000	0.900	59.5000	0.902	59.5000	0.904	59.5000	0.905
59.6000	0.896	59.6000	0.899	59.6000	0.902	59.6000	0.904	59.6000	0.905
Minimum	0.890	Minimum	0.896	Minimum	0.899	Minimum	0.902	Minimum	0.904
Maximum	0.896	Maximum	0.900	Maximum	0.902	Maximum	0.904	Maximum	0.906
Mean	0.893	Mean	0.898	Mean	0.901	Mean	0.903	Mean	0.905

Trial 1

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
58.8000	0.900	58.8000	0.904	58.8000	0.905	58.8000	0.900	58.8000	0.903
58.9000	0.900	58.9000	0.904	58.9000	0.905	58.9000	0.900	58.9000	0.903
59.0000	0.900	59.0000	0.904	59.0000	0.905	59.0000	0.900	59.0000	0.903
59.1000	0.900	59.1000	0.904	59.1000	0.905	59.1000	0.900	59.1000	0.903
59.2000	0.900	59.2000	0.904	59.2000	0.905	59.2000	0.900	59.2000	0.903
59.3000	0.900	59.3000	0.904	59.3000	0.905	59.3000	0.900	59.3000	0.903
59.4000	0.900	59.4000	0.904	59.4000	0.905	59.4000	0.900	59.4000	0.903
Minimum	0.891	Minimum	0.900	Minimum	0.904	Minimum	0.900	Minimum	0.903
Maximum	0.900	Maximum	0.904	Maximum	0.906	Maximum	0.905	Maximum	0.905
Mean	0.897	Mean	0.902	Mean	0.905	Mean	0.901	Mean	0.904

Trial 2

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
58.6000	0.889	58.6000	0.893	58.6000	0.893	58.6000	0.894	58.6000	0.906
58.7000	0.889	58.7000	0.893	58.7000	0.894	58.7000	0.894	58.7000	0.907
58.8000	0.889	58.8000	0.894	58.8000	0.893	58.8000	0.894	58.8000	0.907
58.9000	0.889	58.9000	0.894	58.9000	0.893	58.9000	0.894	58.9000	0.906
59.0000	0.889	59.0000	0.894	59.0000	0.893	59.0000	0.894	59.0000	0.906
59.1000	0.889	59.1000	0.893	59.1000	0.893	59.1000	0.894	59.1000	0.906
59.2000	0.889	59.2000	0.893	59.2000	0.893	59.2000	0.894	59.2000	0.906
Minimum	0.879	Minimum	0.889	Minimum	0.891	Minimum	0.892	Minimum	0.894
Maximum	0.889	Maximum	0.894	Maximum	0.894	Maximum	0.905	Maximum	0.907
Mean	0.885	Mean	0.891	Mean	0.892	Mean	0.897	Mean	0.902

Trial 3

At temperature 70 (battery)

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.2000	0.900	59.2000	0.897	59.2000	0.897	59.2000	0.897	59.2000	0.900
59.3000	0.900	59.3000	0.897	59.3000	0.897	59.3000	0.897	59.3000	0.900
59.4000	0.900	59.4000	0.897	59.4000	0.897	59.4000	0.897	59.4000	0.900
59.5000	0.900	59.5000	0.897	59.5000	0.897	59.5000	0.897	59.5000	0.900
59.6000	0.900	59.6000	0.897	59.6000	0.897	59.6000	0.897	59.6000	0.900
59.7000	0.900	59.7000	0.897	59.7000	0.897	59.7000	0.897	59.7000	0.900
59.8000	0.900	59.8000	0.897	59.8000	0.897	59.8000	0.897	59.8000	0.900
Minimum	0.895	Minimum	0.896	Minimum	0.897	Minimum	0.897	Minimum	0.896
Maximum	0.901	Maximum	0.900	Maximum	0.898	Maximum	0.898	Maximum	0.901
Mean	0.898	Mean	0.898	Mean	0.897	Mean	0.897	Mean	0.898

Trial 1

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
57.8000	0.897	57.8000	0.897	57.8000	0.897	57.8000	0.897	57.8000	0.897
57.9000	0.897	57.9000	0.897	57.9000	0.897	57.9000	0.897	57.9000	0.897
58.0000	0.897	58.0000	0.897	58.0000	0.897	58.0000	0.897	58.0000	0.897
58.1000	0.897	58.1000	0.897	58.1000	0.897	58.1000	0.897	58.1000	0.897
58.2000	0.897	58.2000	0.897	58.2000	0.897	58.2000	0.897	58.2000	0.897
58.3000	0.897	58.3000	0.896	58.3000	0.897	58.3000	0.897	58.3000	0.897
58.4000	0.897	58.4000	0.897	58.4000	0.897	58.4000	0.897	58.4000	0.897
Minimum	0.896	Minimum	0.896	Minimum	0.896	Minimum	0.897	Minimum	0.897
Maximum	0.897	Maximum	0.897	Maximum	0.897	Maximum	0.897	Maximum	0.897
Mean	0.897	Mean	0.896	Mean	0.896	Mean	0.897	Mean	0.897

Trial 2

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.4000	0.896	59.4000	0.896	59.4000	0.896	59.4000	0.896	59.4000	0.896
59.5000	0.896	59.5000	0.896	59.5000	0.896	59.5000	0.896	59.5000	0.896
59.6000	0.896	59.6000	0.896	59.6000	0.895	59.6000	0.895	59.6000	0.896
59.7000	0.896	59.7000	0.896	59.7000	0.896	59.7000	0.896	59.7000	0.896
59.8000	0.896	59.8000	0.896	59.8000	0.896	59.8000	0.896	59.8000	0.896
59.9000	0.896	59.9000	0.896	59.9000	0.896	59.9000	0.896	59.9000	0.896
60.0000	0.896	60.0000	0.896	60.0000	0.896	60.0000	0.896	60.0000	0.896
Minimum	0.896	Minimum	0.895	Minimum	0.895	Minimum	0.895	Minimum	0.896
Maximum	0.897	Maximum	0.896	Maximum	0.896	Maximum	0.896	Maximum	0.896
Mean	0.896	Mean	0.896	Mean	0.895	Mean	0.895	Mean	0.895

Trial 3

At temperature 70 (ultracapacitor)

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.3000	0.875	59.3000	0.881	59.3000	0.876	59.3000	0.878	59.3000	0.873
59.4000	0.874	59.4000	0.881	59.4000	0.876	59.4000	0.877	59.4000	0.872
59.5000	0.874	59.5000	0.881	59.5000	0.875	59.5000	0.877	59.5000	0.872
59.6000	0.873	59.6000	0.881	59.6000	0.875	59.6000	0.877	59.6000	0.871
59.7000	0.873	59.7000	0.879	59.7000	0.875	59.7000	0.877	59.7000	0.871
59.8000	0.873	59.8000	0.877	59.8000	0.875	59.8000	0.877	59.8000	0.870
59.9000	0.873	59.9000	0.877	59.9000	0.875	59.9000	0.877	59.9000	0.871
Minimum	0.865	Minimum	0.854	Minimum	0.863	Minimum	0.862	Minimum	0.861
Maximum	0.883	Maximum	0.884	Maximum	0.882	Maximum	0.881	Maximum	0.881
Mean	0.874	Mean	0.875	Mean	0.875	Mean	0.872	Mean	0.872

Trial 1

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.4000	0.866	59.4000	0.879	59.4000	0.861	59.4000	0.874	59.4000	0.872
59.5000	0.866	59.5000	0.879	59.5000	0.860	59.5000	0.874	59.5000	0.874
59.6000	0.866	59.6000	0.879	59.6000	0.860	59.6000	0.875	59.6000	0.877
59.7000	0.866	59.7000	0.879	59.7000	0.860	59.7000	0.875	59.7000	0.880
59.8000	0.866	59.8000	0.879	59.8000	0.860	59.8000	0.875	59.8000	0.882
59.9000	0.866	59.9000	0.878	59.9000	0.860	59.9000	0.875	59.9000	0.882
60.0000	0.866	60.0000	0.878	60.0000	0.860	60.0000	0.875	60.0000	0.882
Minimum	0.855	Minimum	0.864	Minimum	0.860	Minimum	0.859	Minimum	0.857
Maximum	0.890	Maximum	0.887	Maximum	0.882	Maximum	0.893	Maximum	0.890
Mean	0.875	Mean	0.875	Mean	0.875	Mean	0.875	Mean	0.871

Trial 2

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.4000	0.860	59.4000	0.861	59.4000	0.861	59.4000	0.874	59.4000	0.881
59.5000	0.861	59.5000	0.862	59.5000	0.862	59.5000	0.873	59.5000	0.881
59.6000	0.861	59.6000	0.862	59.6000	0.862	59.6000	0.872	59.6000	0.879
59.7000	0.861	59.7000	0.862	59.7000	0.862	59.7000	0.871	59.7000	0.878
59.8000	0.861	59.8000	0.862	59.8000	0.862	59.8000	0.871	59.8000	0.878
59.9000	0.861	59.9000	0.862	59.9000	0.862	59.9000	0.872	59.9000	0.878
60.0000	0.863	60.0000	0.863	60.0000	0.862	60.0000	0.872	60.0000	0.878
Minimum	0.857	Minimum	0.858	Minimum	0.857	Minimum	0.856	Minimum	0.855
Maximum	0.890	Maximum	0.890	Maximum	0.890	Maximum	0.881	Maximum	0.867
Mean	0.870	Mean	0.872	Mean	0.874	Mean	0.870	Mean	0.872

Trial 3

At temperature 70 (B-UC combination)

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
59.2000	0.895	59.2000	0.897	59.2000	0.898	59.2000	0.900	59.2000	0.899
59.3000	0.895	59.3000	0.897	59.3000	0.898	59.3000	0.900	59.3000	0.899
59.4000	0.895	59.4000	0.897	59.4000	0.898	59.4000	0.900	59.4000	0.899
59.5000	0.895	59.5000	0.897	59.5000	0.898	59.5000	0.900	59.5000	0.899
59.6000	0.895	59.6000	0.897	59.6000	0.898	59.6000	0.900	59.6000	0.899
59.7000	0.895	59.7000	0.897	59.7000	0.898	59.7000	0.900	59.7000	0.900
59.8000	0.895	59.8000	0.897	59.8000	0.898	59.8000	0.900	59.8000	0.900
Minimum	0.891	Minimum	0.895	Minimum	0.897	Minimum	0.895	Minimum	0.897
Maximum	0.895	Maximum	0.897	Maximum	0.898	Maximum	0.901	Maximum	0.900
Mean	0.893	Mean	0.896	Mean	0.898	Mean	0.898	Mean	0.899

Trial 1

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
58.2000	0.892	58.2000	0.896	58.2000	0.897	58.2000	0.897	58.2000	0.897
58.3000	0.892	58.3000	0.896	58.3000	0.897	58.3000	0.897	58.3000	0.897
58.4000	0.892	58.4000	0.896	58.4000	0.897	58.4000	0.897	58.4000	0.897
58.5000	0.892	58.5000	0.896	58.5000	0.897	58.5000	0.897	58.5000	0.897
58.6000	0.892	58.6000	0.896	58.6000	0.897	58.6000	0.897	58.6000	0.897
58.7000	0.893	58.7000	0.896	58.7000	0.897	58.7000	0.897	58.7000	0.897
58.8000	0.892	58.8000	0.896	58.8000	0.897	58.8000	0.897	58.8000	0.897
Minimum	0.879	Minimum	0.892	Minimum	0.896	Minimum	0.897	Minimum	0.897
Maximum	0.893	Maximum	0.896	Maximum	0.897	Maximum	0.897	Maximum	0.897
Mean	0.888	Mean	0.894	Mean	0.896	Mean	0.897	Mean	0.897

Trial 2

Current, Ch A Run #1		Current, Ch A Run #2		Current, Ch A Run #3		Current, Ch A Run #4		Current, Ch A Run #5	
Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)	Time (s)	Current (A)
58.8000	0.884	58.8000	0.889	58.8000	0.893	58.8000	0.897	58.8000	0.898
58.9000	0.884	58.9000	0.889	58.9000	0.893	58.9000	0.897	58.9000	0.898
59.0000	0.884	59.0000	0.889	59.0000	0.893	59.0000	0.897	59.0000	0.898
59.1000	0.884	59.1000	0.889	59.1000	0.893	59.1000	0.897	59.1000	0.898
59.2000	0.884	59.2000	0.889	59.2000	0.893	59.2000	0.897	59.2000	0.898
59.3000	0.884	59.3000	0.889	59.3000	0.893	59.3000	0.897	59.3000	0.898
59.4000	0.884	59.4000	0.889	59.4000	0.893	59.4000	0.897	59.4000	0.898
Minimum	0.874	Minimum	0.884	Minimum	0.889	Minimum	0.894	Minimum	0.897
Maximum	0.901	Maximum	0.889	Maximum	0.894	Maximum	0.897	Maximum	0.898
Mean	0.884	Mean	0.887	Mean	0.891	Mean	0.896	Mean	0.898

Trial 3